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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	31 Oct 94	Final Report 2 May 94 - 31 Oct 94

4. TITLE AND SUBTITLE
Development of Anthropometric Analogous Headforms

5. FUNDING NUMBERS
C-DAMD17-94-C-4065

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8. PERFORMING ORGANIZATION REPORT NUMBER
941001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of the Army
U.S. Army Medical Research
and Materiel Command
Fort Detrick, Frederick, MD 21702-5012

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
* University of Michigan, Ann Arbor, Michigan

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Designing small, medium and large headforms for retention and fit assessment of military helmets was the study's central objective. Using the U.S. Anthropometric Survey, a multivariate procedure for sizing yielded three sets of optimal values for four independent, head and face variables. The remaining variables were set at the median values from three subpopulations (each 5% of the total population) centered about the optimal sets. Other reported data includes inertial properties, skin properties, CAD renderings and waterline cross-sectional geometries.

14. SUBJECT TERMS
Anthropometric Headforms; Multivariate Analysis; Surface Modeling; Dummy; Manikin; Head; Face; Helmet; Percentiles; Retention; Fit

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Limited

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AD_______________

CONTRACT NO: DAMD17-94-C-4065

TITLE: DEVELOPMENT OF ANTHROPOMETRIC ANALAGOUS HEADFORMS

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REPORT DATE: October 31, 1994

TYPE OF REPORT: Phase I Final Report

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick
Frederick, Maryland 21702-5012

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Principal Investigator's Signature

October 28, 1994
Date

DAMD17-94-C-4065

ACKNOWLEDGMENT

Dr. Claire C. Gordon and Steven Paquette of U.S. Army Natick Research, Development and Engineering Center made significant contributions to this study not only by making ANSUR data available, but also providing consultation throughout the course of the effort. Dr. Brian Corner of GEO-CENTERS, Inc., who prepared the data files of head and face variables and landmark coordinate data, gave valuable assistance in using the data. Dr. Herbert M. Reynolds of the Biomechanics Department at Michigan State University provided helpful guidance and suggestions about anthropometric modeling, and analysis of anthropometric data. Finally, Mr. B. Joseph McEntire, COTR, U.S. Army Aeromedical Research Laboratory, made the entire effort possible by his encouragement and support. The authors gratefully acknowledge all their contributions.

EXECUTIVE SUMMARY

This report describes the effort leading to the development of designs for three manikin headforms--small, medium, and large--for use in military ejection seat and crashworthiness testing, as well as retention and fit assessment of helmet and head-supported devices. The headform geometries are derived from combined military male and female aviator population data, and interface with the Hybrid III-family dummies.

A literature review identified the U.S. Army Anthropometric Survey (ANSUR) as the most appropriate database for developing the headform surface geometry and properties for several reasons: because of the currency of the data, accuracy due to computerized data acquisition and reduction, inclusion of head and face landmark data, availability of data for individual subjects, and inclusion of separate male and female populations.

A major task of the design effort was to establish the three-dimensional surface geometry of the face and head for the three headform sizes. For this purpose, a multivariate procedure was developed to identify optimal values for the three sizes, of selected independent variables including the head length, breadth, circumference, and a facial length--the menton-to-sellion (nasion) distance. From a combined male and female database, the methodology was used to identify the optimal values of the four independent variables, for the three sizes, based on representation of the 5th percent, 50th percent, and 95th percent populations. Three subpopulations, each of a size of 5% of the total population, and centered about the derived optimal values, were identified. The median values for all other head and face (dependent) variables were determined for each subpopulation and used to develop the corresponding headform.

Other head properties for which headform design specifications were developed include head mass, head principal moments of inertia, locations of the head center of gravity and the head-neck pivot point (the occipital condyles), and friction and force-deflection properties of the headform surface. Data include values reported in the literature for cadaver studies and for the Hybrid III crash dummy. Since the Hybrid III design was based on the best available cadaver data, the present headform specifications, with the exception of surface geometry and principal axes of inertia, were selected to be the same as for the Hybrid III headform.

Creation of the three manikin headform designs was accomplished using the AutoCAD computer-aided design package. A total of 48 linear head dimensions were used to locate the positions of 26 facial landmarks. Landmark positions were entered as three dimensional data points in reference to a user-defined local coordinate system. A headform wireframe was created through the facial landmarks from a system of spline entities. The AutoSurf surface modeling system was then used to generate surfaces between closed sections of the headform wireframe. Separate skin and skull surface layers were generated for each of the three sizes of headforms. In addition to rendering the headform images, the shapes of the headforms were described using waterlines and a headform coordinate system, and the exterior dimensions of each headform skin and skull surface were presented in tabular form. The AutoCAD software is capable of producing output files that accurately describe the headform surfaces in the IGES format, and these files can be used effectively in the fabrication and machining of solid models from computer based designs.

TABLE OF CONTENTS

1.0 INTRODUCTION

Modern combat aircraft such as the Blackhawk incorporate various weapons systems which require significant aviator proficiency. Missions such as Nap-of-the-Earth (NOE), Night Vision Goggle (NVG) operations, anti-armor and chemical warfare, and air-to- air/air-to-ground combat pose requirements on the helmet which are complex in terms of helmet-mounted equipment. Some of the resulting helmet characteristics, including excessive weight and moments of inertia, bulkiness, improper location of center of gravity, poor helmet retention, inadequate integration with goggles and the helmet sight assembly (HSA), can all be major factors in degrading aviator performance. Also, the helmet is the most ubiquitous form of head protection and as such it must perform well in reducing the severity and probability of injuries to the head.

There are two basic uses of manikins in relation to head dynamic response in high-G, aviation environments, e.g., rotary-wing crashes and fixed-wing ejections. One is to predict the likelihood or severity of injuries to the head, face, or neck that can occur for an aviator subjected to the same high-G conditions as experienced by a test manikin. The second is to evaluate the effectiveness and fit of helmets, masks, and goggles in conditions of high-G responses of the head. Conditions of direct impact loading and also non-contact, inertial loading are pertinent to both of these basic uses.

It is not necessary, however, to use a complete manikin in all experimental studies related to the aforementioned operational factors. Indeed, free-fall and pendulum impact tests of manikin heads alone provide, for many purposes, the most directly meaningful experimental results. Such tests are relatively easily conducted, results are sometimes more easily interpreted, and test conditions and responses are easily controlled and replicated. For these purposes, there are four basic areas of engineering design in which headforms must satisfactorily mimic the human head. These are: 1. anthropometry (dimensions and surface geometry of the face and skull); 2. mass properties (mass, principal moments of inertia, location of center of mass, and orientation of the principal axes of inertia); 3. "skin" and "dura" mechanical properties (primarily, force-deflection characteristics); and 4. location of the occipital pivot at which the head connects to the manikin's neck module. To develop such headforms, therefore, the overall technical objectives of this Phase I study include:

1. An in-depth review of relevant literature and identification of a database suitable for representing the aviator population of interest;

2. Development of methodologies for characterizing the extremes of a population.

3. Analysis and derivation of anthropometric measures for the proposed small, medium and large headforms;

4. Sculpture of headform and skullform surfaces, from anatomical landmarks and other anthropometric measures, using a CAD system;

5. Development of mass distribution properties, skin properties and occipital pivot location for the headforms;

6. Selection of materials suitable for skin and skullform fabrication; and,

7. Identification of fabrication technologies which interface directly to CAD files in the IGES format.

2.0 SELECTION OF ANTHROPOMETRIC DATABASE

An extensive literature review was conducted on anthropometric databases. Only the major considerations leading to the selection of a specific anthropometric survey as a database for headform sizing is discussed herein. Additional details are included in Appendix A.

The literature search identified three military anthropometric projects as being of potential usefulness in the current study. These are: 1. the Tri-Service database, 2. the CARD database, and 3. the ANSUR database. The database selected for use in the study is the ANSUR database.

TRI-SERVICE Database. The Tri-Service database is described and documented in [*Anthropometry...*, 1988]. The data represents 3rd, 50th, and 95th percent aircrew as defined from stature and weight multiple regression equations. (X,Y,Z) data for anatomical landmarks are not given; only "standard" anthropometric dimensional measurements are available.

The unavailability of (X,Y,Z) data for anatomical landmarks and the implicit assumption of a proportional dependence of head and face dimensions on stature and weight are factors which make the Tri-Service database of questionable usefulness for the present study. An additional factor is that the database includes no data for female subjects, which need to be utilized in the current study.

CARD Database. The Anthropometric Database at the U.S. Air Force Computerized Anthropometric Research and Design (CARD) Laboratory, is described in [Robinson, 1992]. The database currently contains nine different surveys, five for Air Force, three for Army and one for Navy. There are databases for both males and females. The earliest survey in the CARD Anthropometric Database is 1965 and the latest is 1977.

The numeric data available are summary statistics and frequency data for each measurement. As with the Tri-Service database, there are no (X,Y,Z) data for anatomical landmarks. Further, as with the Tri-Service database, data for individual subjects does not seem to be available. These two factors, together with the fact that the data are 20-30 years old and thus not entirely representative of the 1990s population, make it doubtful that this database could be used effectively to meet the particular goals of the current study.

ANSUR Database. The U.S. Army Anthropometric Survey (ANSUR), conducted in 1987-1988, is described in [Natick, 1989-91;Hubbard, 1974]. Measurement data for 1,774 men and 2,208 women comprise the working database.

Several factors make the ANSUR data more suitable for the present study than either the Tri-Service data, or the CARD data: First, the currency of the data; second, inclusion of separate male and female groups; third, availability of "raw" data for head and face dimensions; and fourth, improved measurement accuracy due to computerized data acquisition. Also, (X,Y,Z) data for head and facial landmarks are available for all subjects, and such data were considered vital for developing the geometry of the headforms.

3.0 METHODOLOGY FOR CHARACTERIZING POPULATION EXTREMES

Representation of a population by one or more headforms requires consideration of the multivariate nature of the population, to define not only the number of headforms required, but also their specific anthropometric features. For this purpose, characterizing the extremes of a population continues to be a challenging problem in engineering anthropometry, and available techniques are not of universal applicability.

Designers of equipment, or workspaces, frequently derive accommodation limits on the basis of univariate percentiles of anthropometric features. Such use of univariate percentiles to characterize a multivariate space can lead to exclusion of greater than the intended population. Moroney [8] notes that use of univariate percentiles mistakenly presupposes that those individuals with an anthropometric measurement outside the established range on one anthropometric measure will be the same individuals who fall outside the established range on all other anthropometric features. That the supposition is clearly false is noted by others (Haselgrave, 1986) as well.

The traditional procedures for dealing with multivariate situations, generally presume a normal distribution in order to make the analysis tractable. For example, for bivariate normal distribution models, Churchill [9] describes the construction of equal probability ellipses and artificial bivariate tables, which in theory can be extended to any number of variables. Another technique, the principal components analysis, described by Kshirsagar [10] and others, is based on determining the eigenvectors of the variance-covariance matrix and selecting a few of the eigenvectors associated with the largest eigenvalues to represent the space. The limitation of all these methods is that the designer still has to exercise considerable judgment to obtain design limits.

3.1 Delineation of sizes

The major objective of this study is to design headforms which can be used for assessing fit and retention for members of the ANSUR population. But before any such design can be undertaken, two basic questions need to be answered: How many headforms? And of what sizing? These questions will be addressed in the remainder of this section.

In simplistic terms, a headform can be useful for the intended purpose only for those helmets which it will accept: i.e. selected key dimensions of the helmet are equal to, or bigger than the respective dimensions of the headform. Though, resiliency of the padding used in helmets provides a range of head sizes which can be covered but not necessarily accommodated, for this discussion a helmet will be presumed to be useful only up to a limiting key head size. If any single key dimension of a helmet is smaller than the corresponding dimension of a given head, then the helmet can be deemed to be unacceptable for that head.

Conversely, if a key dimension of a head from a given population is bigger than the corresponding dimension of a headform, then the headform cannot be a surrogate for that head. Thus, the argument can be advanced that if one headform alone is to represent a whole population group, then its key dimensions must be such that it is the smallest surrogate for the most number of members in that group. Conventional wisdom would say that the headform probably should be centered; perhaps about the mean, median, or cover 50% of the population in some way. The fallacy here is that if a headform is sized to be centered in the population, then it is unsuitable for use with helmets which are sized for fitting the smaller half of the population. Clearly, the headform has to be smaller than the indications from measures of central tendency, to cover the maximum possible number of members of the group.

To formalize this argument, it is convenient to treat the key dimensions as random variables. Recall the definition of a continuous random variable X over the sample space $0 \leq x \leq 1$: the probability P that X assumes a value in the interval $0 \leq a,b \leq 1$ is given by

$$P(a<X<b) = \int_a^b f(x)dx$$

where, the probability density function f(x) has the properties:

$$f(x) \geq 0 \quad \text{and} \quad \int_0^1 f(x)dx = 1$$

Similarly, a cumulative distribution function F for the random variable is given by

$$F(x) = P(X \leq x) = \int_0^x f(u)du$$

Also, recall that for joint distributions of several random variables, single integrals become multiple integrals of corresponding dimensions.

To fix ideas, given two random variables for headform sizing, $\underline{Xmin} \leq \underline{X} \leq \underline{Xmax}$ and $\underline{Ymin} \leq \underline{Y} \leq \underline{Ymax}$, the relevant data can be mapped into the normalized sample space of $0 \leq x \leq 1$ and $0 \leq y \leq 1$ by the transformation

$$x = (\underline{X} - \underline{Xmin})/(\underline{Xmax} - \underline{Xmin})$$
$$y = (\underline{Y} - \underline{Ymin})/(\underline{Ymax} - \underline{Ymin})$$

(The purpose of the normalization is twofold: To remove dimensional dissimilarity such as between height, area, volume, or weight, and preserve numerical accuracy in computations.)

The mapping produces the familiar scatter plot, but in a square of unit area, with the population distributed into bins whose size is determined by the number of divisions selected along each axis. The variables now become discrete, and may be treated as such for the purposes of computer implementation; however, they will be regarded as continuous for purposes of this discussion. Using the binned values at (x,y), the probability density function f(x,y) can be determined from:

$$f(x,y) = n/(N.\Delta x.\Delta y)$$

where n is the binned population count, N is the total population count and Δx, Δy, are the binning intervals.

The cumulative distribution function F(x,y) is given by

$$F(x,y) = P(X \leq x, Y \leq y) = \int_0^x \int_0^y f(u,v)dudv$$

Note that 100*F(x,y) represents a percent value of the total population and this subpopulation has key dimensions X and Y such that $X \leq x$, and $Y \leq y$.

An average probability density, d, can be defined as

$$d(x,y) = F(x,y)/xy$$

If d(x1,y1) is a maximum anywhere in the sample space, then x1 and y1 are key dimensions which define the smallest surrogate for the largest population.

Implementation of the procedure for multidimensional, normalized sample space is made simpler by the following procedure.

For variables X_i, i=1 to m, if f is the probability function, then find x_i, i=1 to m, such that I is a minimum, where

$$I = \int_0^{X_1}\int_0^{X_2}\ldots\int_0^{X_m} du_1\, du_2 \ldots du_m$$

subject to the constraint of a selected value of F as

$$F = \int_0^{X_1}\int_0^{X_2}\ldots\int_0^{X_m} f(u_1, u_2, \ldots u_m) du_1 du_2 \ldots du_m$$

The above is a constrained minimization problem that can be solved by several techniques from the field of optimization. Also, the constrained minimization problem can be reduced to one which is unconstrained by introducing slack variables. Related details can be found in many publications, including one by Aoki [11]. The major obstacle in implementing these procedures is computation of local derivatives of f up to the second order, depending on the method selected. While this is not a major problem, an algorithm which fits more readily into computations with binned data is described in terms of bivariate data. The procedure is readily generalized to multivariate data.

																					Sum
20	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
19	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
17	0	0	0	0	0	2	0	0	2	1	1	1	1	0	1	0	0	0	0	1	10
16	0	0	1	3	1	1	2	1	4	4	6	3	1	1	1	0	1	0	1	0	31
15	1	0	0	0	1	5	6	2	4	10	7	7	3	3	4	1	0	1	0	0	55
14	0	1	1	1	2	1	2	4	3	11	15	8	9	9	5	0	0	2	1	0	75
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11	0	2	1	2	8	15	15	17	45	26	35	32	21	23	14	6	3	0	3	1	269
10	0	0	5	1	4	15	17	25	41	33	40	32	26	16	6	3	2	0	0	0	266
9	1	0	3	0	7	13	11	24	31	23	41	27	14	12	4	2	0	1	0	0	214
8	1	1	0	3	6	17	15	21	37	26	33	34	14	12	5	1	3	0	0	0	229
7	1	0	1	0	3	5	6	8	17	12	10	8	5	2	2	4	0	0	0	0	84
6	0	1	0	0	2	5	4	2	6	4	6	2	1	2	0	1	0	0	0	0	36
5	0	0	1	1	1	1	1	5	3	1	2	1	0	1	0	0	0	0	0	0	18
4	0	0	0	1	0	1	2	1	3	2	1	0	0	0	0	0	1	0	0	0	12
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Sum	5	5	20	18	45	100	105	145	257	205	259	204	137	120	55	32	17	5	7	2	1743
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

Figure 1. Bivariate Chart for Breadth Vs. Length

To illustrate the process, the scatter plot for head length and head breadth from the ANSUR data for males is shown in figure 1. The search begins at the point which represents the maximum for all variables and proceeds in steps into the interior of the space. The direction of each step is selected such that it results in the least reduction of population in the remaining space. If all directions yield the same reduction in population, then the direction is selected to obtain maximum reduction in sample space. This process is greatly aided by keeping marginal distributions for each variable and updating them at each step to represent the remaining population only. (In terms of the minimization procedure described earlier, the marginal distributions give the local derivatives for each variable.) The resulting trajectory of the search is shown by the shaded area. At each step, the percent of the remaining population, values of the variables, and the average probability density in the remaining sample space, are recorded.

3.2 Subpopulations

If only one headform is to be used to represent a population, then the location of the maximum average probability density in the sample space provides the required key dimensions. When more than one headform is desired, however, additional considerations are needed. An obvious choice is to split the population into subpopulations on some basis and apply the procedure separately to each of the subpopulations. For example, the population may be sorted into the required number of subgroups by the magnitude of the product of the selected variables. Another choice is simply to proceed along the search trajectory for the whole population and use the dimensions recorded for selected percentages of the population. The latter method was selected for use in this effort, as described subsequently.

3.3 Dependent variables

So far, the discussion centered around identifying key dimensions based on selected independent variables, which of necessity have to be few. (Computer memory requirements for the described method increases with the number of variables as an exponent.) Once the key independent dimensions are established, there is still the question of how the others, which may be called dependent, are to be selected.

Linear multiple regression has been used extensively for modeling dependent variables. However, as noted by Haslegrave (1986), it does not always lead to dimensions which could be representative of a real person. Consequently, Haslegrave recommends that once the values of the independent variables are established, a group of people having those values be assembled, measured and median values determined for all other dependent variables. This approach was adopted for the present effort in a modified form as follows:

Once the location of the desired set of values for independent variables was identified on the search trajectory, members closest to that point were identified by sweeping the space with an increasing radius until a predetermined number of members were assembled. The data for these members was then screened to establish the medians for all the dependent variables. The cluster assembled for the purposes of the present study, as described later, included 5% of the population centered about each trajectory point of interest

3.4 Selection of Independent Variables

Whatever approach is used for anthropometric modeling, it is necessary to select some small number of variables as primary. These variables, the independent variables of the model, are the ones that are used for predicting estimates for all of the other variables. Variables that are suitable to serve as independent variables must satisfy two basic criteria. First, they should in some way represent specific, unrelated but basic characteristics of the anthropometry. Second, they need to be related, singly or collectively, to all of the remaining dependent variables.

Hubbard and McLeod (1973; pg. 130) cite a study by Churchill and Truett (1957) in which it was found that there is very low correlation ($r = 0.12$) between head length and head breadth. Such primary variables are good candidates for roles as independent variables, assuming that in addition to low correlation to each other, they have relatively higher correlation to a significant number of other variables in the database. Hubbard and McLeod also note that the Churchill-Truett study documents a generally poor correlation between dimensions of the head and face. This is found also by McConville and Alexander (1972; pg. 24) and by Cheverud, et al. (1990; Parts 2-5). Thus, in addition to head variables, a length for some facial feature may well be suitable for use as an independent variable.

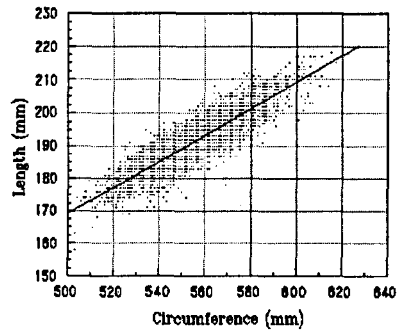
Using the combined ANSUR male and female data, combinations of the following variables were investigated for use as independent variables in the present study: head length, head breadth, head circumference, menton-to-sellion length, and menton-to-top-of-head length. The scatter plots for pairs of these variables, with superimposed straight lines from linear regression, are illustrated in figures 2a through 2i. The regression data for the straight lines are given in table 1. Values of the correlation coefficient, r, exceeding 0.6 indicates that both the head length and breadth are correlated to circumference; the former strongly, and the latter moderately. Also, menton-to-top-of-head length appears to be moderately correlated to head length and head circumference. Though elimination of head circumference as an independent variable would simplify the model, because it is widely specified as a helmet design variable, an arbitrary decision was made to retain it in the subsequent analyses with the ANSUR data. These analyses are based on three sets of independent variables, as follows:

- Set 1: Head length, head breadth, head circumference and menton-sellion length.
- Set 2: Head length, head breadth, head circumference and menton-top-of-head length.
- Set 3: Head length, head breadth, head circumference.

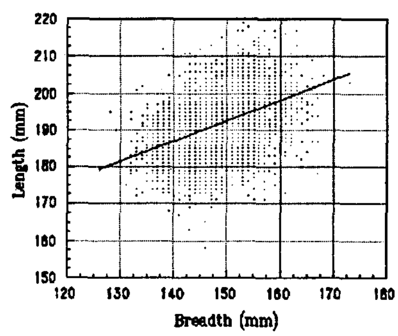
Results from using these sets are described in the next section.

Table 1. Correlation between pairs of variables.

	Dependent Variable y	Independent Variable x	Correlation Coefficient r	Regression Line Parameters y=Ax+B A	B(mm)
(a)	Length	Circumference	0.8825	0.3998	-30.5939
(b)	Length	Breadth	0.4190	0.5573	109.3109
(c)	Breadth	Circumference	0.6759	0.2302	19.6835
(d)	Menton-Sellion	Length	0.5524	0.4971	21.9491
(e)	Menton-Sellion	Breadth	0.4129	0.4942	44.2282
(f)	Menton-Sellion	Circumference	0.5606	0.2286	-9.8263
(g)	Menton-Top of Head	Length	0.6479	0.8742	56.4583
(h)	Menton-Top of Head	Breadth	0.5396	0.9685	80.9830
(i)	Menton-Top of Head	Circumference	0.6888	0.4211	-10.0595



(a)



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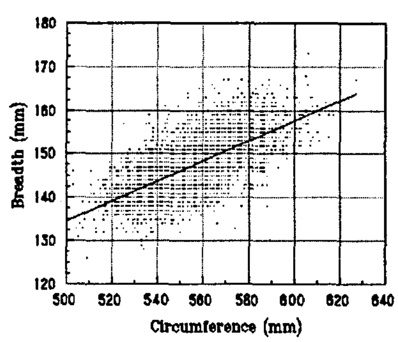
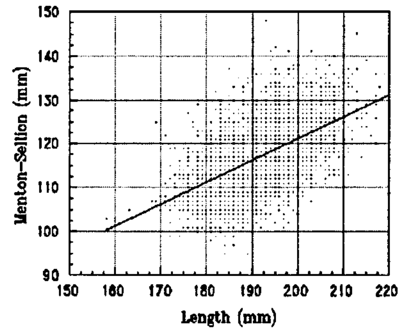
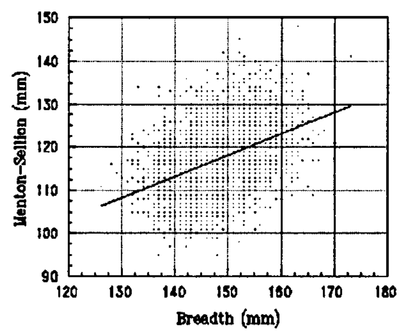


(c)

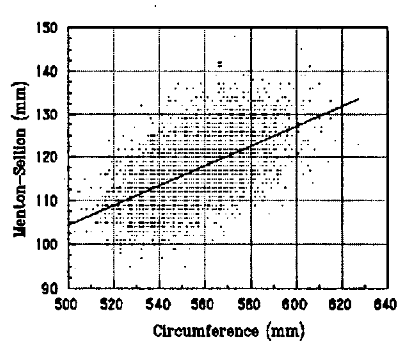
Figure 2. Linear Regression Correlation of Independent Values



(d)

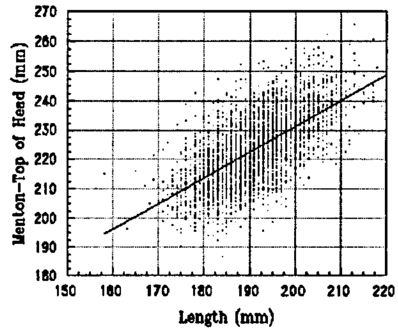


(e)

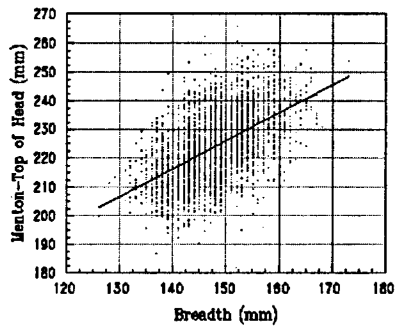


(f)

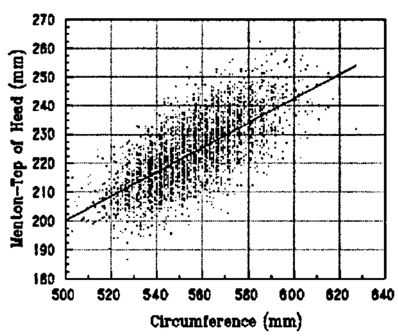
Figure 2. Linear Regression Correlation of Independent Values



(g)



(h)



(i)

Figure 2. Linear Regression Correlation of Independent Values

4.0 MULTIVARIATE LIMIT ANALYSIS COMPUTER PROGRAMS

Four computer programs were written by CTI to develop dimensions for the three headforms (small, medium, and large). The dimensions for the headforms are based on median values for groups of subjects selected by a multivariate limit analysis developed by CTI. The programs were written to handle between two and four independent variables using the analysis method described in the previous section.

The computer programs were written in FORTRAN 77, but included some Fortran 90 extensions, and were compiled and linked using Lahey FORTRAN EM/32 which uses an extended DOS environment on a personal computer. The extended DOS environment was necessary to handle the large number of subjects included in the analysis.

The analyses were completed in four steps with a program written to perform each of the steps. This provided CTI the ability to test several different theoretical methods for the analyses in a time efficient manner. The four programs, *HF_LGTHS, HF_DESC4, HF_GROUP, HF_CMPVS,* will be described below in their order of utilization.

HF_LGTHS: The values contained in the original ANSUR head/neck data files received by CTI included coordinate data referenced to the top and back plane of an automated headboard device. To work efficiently with the multivariate limit analysis, the coordinate data were transformed into lengths that conform with the "visual index - head measurements" used by NATICK. The remaining data were the standard head/neck measurements and conformed with the NATICK reports.

The HF_LGTHS program reads the ANSUR data files and transforms the coordinate positions of the facial landmarks to their appropriate lengths and outputs the results to a file. The program also outputs a file containing a table of values for independent variables used in the multivariate limit analysis. This file is prepared for use with the HF_DESC4 program.

HF_DESC4: The multivariate limit analysis procedure is contained within this program. It gives the user the ability to choose the number of independent variables as well as which independent variables should be used given the ones provided by the HF_LGTHS program. Once the user chooses the independent variables, the program reads the independent variables from the file, computes binning values, and bins each subject based on their independent values. The program then travels through the bins iteratively based on the previously described multivariate limit analysis method. Once the iterations are complete, the program linearly interpolates between nearest iterations to determine the 5th, 50th, and 95th percent values for the independent variables. These values for the independent variables correspond to the small, medium, and large headform sizes respectively.

Now, for each headform size, HF_DESC4 finds the closest five percent of the population to the values based on the independent variables. Subject numbers for each headform size are output to a file for use by the HF_GROUP program.

HF_GROUP: The function of this program is to create three files containing all of the headform measurements for the subjects included in the groupings found by the HF_DESC4 program. HF_GROUP reads the file created by HF_DESC4 and the file of lengths created by HF_LGTHS. It then finds the subjects included for each headform size (small, medium, and large) and writes a file with each subjects dimensions that are included in the group. These files are prepared for use by the HF_CMPVS program.

HF_CMPVS: For each headform (small, medium, and large), HF_CMPVS computes dimensions based on the groupings determined by HF_DESC4. It determines the median values for all head and face dimensions from the files created by HF_GROUP. In addition, HF_CMPVS computes the mean and standard deviation of each dimension for comparison purposes. The program outputs a file which includes a table of means, standard deviations, and medians of all head measurements for each headform size.

4.1 Multivariate Limit Analysis Summary

Three separate analyses were completed using the computer programs discussed in the preceding section. The first analysis method used four independent variables; head length, head breadth, head circumference, and Menton-Sellion length. Use of the Menton-Sellion was motivated by the finding that facial features, in general, correlate poorly with those for the head. The iterative process used in the multivariate limit analysis is shown in table 2 for the first analysis method. As seen in the table, the maximum average probability density occurs after 39 iterations with approximately 41 percent of the population smaller than the current bin values (values of head length, breadth, circumference, and menton-sellion).

Table 2. Example of Multivariate Limit Analysis Iterations for Method 1.

Iteration #	Percent	Binning Indices for each Analysis Dimension				Average Probability Density
0	100.00	20	20	20	20	1.00000
1	99.97	20	19	20	20	1.05236
2	99.95	20	18	20	20	1.11055
3	99.92	20	18	20	19	1.16870
4	99.90	20	18	20	18	1.23332
5	99.87	20	18	19	18	1.29790
6	99.80	20	18	18	18	1.36896
7	99.70	20	18	18	17	1.44802
8	99.52	19	18	18	17	1.52152
9	99.37	19	18	17	17	1.60855
10	99.21	18	18	17	17	1.69532
11	98.99	18	18	17	16	1.79714
12	98.71	18	17	17	16	1.89749
13	98.30	18	16	17	16	2.00780
14	97.85	18	16	16	16	2.12339
15	97.44	17	16	16	16	2.23898
16	97.03	17	16	15	16	2.37831
17	96.40	17	16	15	15	2.52030
18	95.59	17	15	15	15	2.66570
19	94.60	17	15	15	14	2.82658
20	93.21	16	15	15	14	2.95899
21	92.27	16	15	14	14	3.13846
22	90.24	15	15	14	14	3.27413
23	88.27	15	15	13	14	3.44876
24	86.57	15	14	13	14	3.62402
25	84.47	15	14	13	13	3.80796
26	82.24	15	13	13	13	3.99260
27	79.68	15	13	12	13	4.19070
28	77.14	14	13	12	13	4.34722
29	74.15	14	13	12	12	4.52693
30	71.31	14	13	12	11	4.74943
31	68.45	14	12	12	11	4.93860
32	65.31	14	12	11	11	5.14023
33	63.10	13	12	11	11	5.34875
34	58.41	13	12	10	11	5.44649
35	54.87	12	12	10	11	5.54199
36	51.42	12	11	10	11	5.66602
37	48.02	12	11	10	10	5.82101
38	44.12	12	11	9	10	5.94217
39	41.05	12	10	9	10	6.08211
40	37.53	11	10	9	10	6.06573
41	33.78	11	10	9	9	6.06618
42	30.01	11	10	9	8	6.06163
43	26.69	11	9	9	8	5.98995
44	24.35	11	9	8	8	6.14994
45	21.95	10	9	8	8	6.09619
46	19.16	10	9	7	8	6.08211
47	15.26	10	9	7	7	5.53504
48	11.71	10	8	7	7	4.77880

Table 2. Example of Multivariate Limit Analysis Iterations for Method 1.

Iteration #	Percent	Binning Indices for each Analysis Dimension				Average Probability Density
49	8.92	10	8	6	7	4.24782
50	7.53	9	8	6	7	3.98233
51	5.83	9	7	6	7	3.52453
52	4.26	9	7	6	6	3.00351
53	3.02	9	7	5	6	2.55298
54	2.43	8	7	5	6	2.31699
55	1.67	8	7	4	6	1.99117
56	1.32	7	7	4	6	1.79291
57	0.96	7	7	4	5	1.57225
58	0.68	7	7	3	5	1.48950
59	0.51	7	6	3	5	1.28722
60	0.38	6	6	3	5	1.12632
61	0.18	6	5	3	5	0.63074
62	0.10	6	5	2	5	0.54063
63	0.05	6	4	2	5	0.33789
64	0.03	6	4	1	5	0.33789

The second analysis method replaced the Menton-Sellion length with the Menton-Top of Head (head height). The final analysis method only used the head length, breadth, and circumference. The three analysis methods were used to compare the dependency of the different dimensions on the overall head size and shape.

For each analysis, a combined data set was utilized (both male and female data) to compute the results. There were 3946 subjects included, this excluded any subject which contained missing information in the original NATICK data. Therefore, the groups of subjects, based on headform size, contained 197 people representing five percent of the total population.

Tables 3-5 contain a summary of the results for each analysis method. They include the values determined by the multivariate limit analysis, the mean, the median, and the standard deviation, for each independent variable. The results are very close for the first two methods and similar but slightly smaller for the third. This represents the difference between using three or four independent variables. Table 6 shows the clustering of subjects based on gender. The analyses demonstrated the anticipated results that the smaller headforms would contain mostly female subjects, and the larger headforms contain mostly male. Tables containing all head and facial measurements appear in appendix ? for the three analysis methods.

Table 3. Small Headform Analysis Summary

Method *see notes below	Value	Head Length (mm)	Head Breadth (mm)	Head Circum-ference (mm)	Menton - Sellion (mm)	Menton - Top of Head (mm)
1	Mult.	185.900	142.450	538.100	112.150	N/A
1	Mean	185.660	142.670	538.827	112.350	215.178
1	Median	186.000	143.000	539.000	112.000	215.100
1	StdDev	2.051	2.226	2.599	2.237	5.919
2	Mult.	185.900	142.450	535.490	N/A	214.420
2	Mean	185.102	142.264	536.442	112.346	214.715
2	Median	185.000	142.000	537.000	111.600	214.600
2	StdDev	2.178	2.393	2.843	4.405	2.989
3	Mult.	185.060	142.450	531.750	N/A	N/A
3	Mean	184.000	141.695	532.964	111.629	213.848
3	Median	184.000	142.000	533.000	111.380	214.100
3	StdDev	2.035	2.002	2.404	5.801	7.725

Table 4. Medium Headform Analysis Summary

Method *see notes below	Value	Head Length (mm)	Head Breadth (mm)	Head Circum-ference (mm)	Menton - Sellion (mm)	Menton - Top of Head (mm)
1	Mult.	195.200	151.850	563.500	123.040	N/A
1	Mean	194.858	151.025	563.447	122.081	230.470
1	Median	195.000	151.000	563.000	122.000	230.100
1	StdDev	2.483	2.580	2.836	2.576	6.038
2	Mult.	195.200	152.260	563.500	N/A	230.200
2	Mean	194.434	151.107	563.538	119.738	229.909
2	Median	195.000	151.000	563.000	119.660	229.600
2	StdDev	2.414	2.652	2.863	4.598	2.906
3	Mult.	195.200	151.850	558.140	N/A	N/A
3	Mean	194.188	150.497	558.726	118.808	227.529
3	Median	194.000	150.000	559.000	118.730	227.100
3	StdDev	1.911	2.104	2.300	5.762	8.011

Table 5. Large Headform Analysis Summary

Method *see notes below	Value	Head Length (mm)	Head Breadth (mm)	Head Circum-ference (mm)	Menton - Sellion (mm)	Menton - Top of Head (mm)
1	Mult.	210.700	161.250	595.250	133.170	N/A
1	Mean	206.411	156.315	591.640	128.036	241.059
1	Median	206.000	156.000	590.000	128.000	241.100
1	StdDev	4.288	3.819	7.065	5.127	8.394
2	Mult.	210.700	161.250	595.250	N/A	246.810
2	Mean	206.355	156.645	591.701	126.031	242.610
2	Median	206.000	156.000	590.000	125.550	241.800
2	StdDev	4.523	4.137	7.613	5.608	6.462
3	Mult.	207.840	161.250	595.250	N/A	N/A
3	Mean	205.695	156.746	591.726	123.862	238.299
3	Median	206.000	156.000	590.000	123.970	237.800
3	StdDev	3.728	3.831	5.853	6.457	9.214

Table 6. Clustering of Subjects Based on Multivariate Method

Method *see notes below	Gender of Subjects: (M)ale (F)emale (3946 Subjects) Small Headform	Medium Headform	Large Headform
1	M:5.1% F:94.9%	M:76.7% F:23.3%	M:97.5% F:2.5%
2	M:4.0% F:96.0%	M:76.1% F:23.9%	M:98.0% F:2.0%
3	M:5.6% F:94.4%	M:73.1% F:26.9%	M:94.9% F:5.1%

Notes for tables 3-6:

- Method 1: Multivariate analysis using head length, head breadth, head circumference, and Menton-Sellion distance.
- Method 2: Multivariate analysis using head length, head breadth, head circumference, and Menton-Top of Head distance.
- Method 3: Multivariate analysis using head length, head breadth, and head circumference.
- "Mult." in value column represents the multivariate analysis results.
- The mean, median, and standard deviation are computed using the cluster of subjects defining the given percent.

5.0 HEAD INERTIAL PROPERTIES

There is an abundance of literature pertaining to the inertial properties of the human head. There is also a large amount of literature pertinent to the inertial properties of anthropomorphic headforms, primarily the Hybrid III dummy. The design values for the headform of the Hybrid III dummy itself represent a compilation of the best available (cadaver) data for midsized human males. Appendix A includes all data found in the literature review of the present study for head mass, head density, and head principal moments of inertia. All Hybrid III data are located at the beginning of the table, followed by all cadaver data.

Except for the direction angles of the principal axes, the inertial properties of the Hybrid III headform will be used as the model for the midsized headform developed in the present study. No additional data have come from any recent studies to improve inertial property specifications for the Hybrid III headform. It is essentially the cadaver data in Appendix A that, collectively, established and corroborated the inertial properties of the current Hybrid III headform.

5.1 Midsized Headform

The headform of the GM ATD 502 crash dummy was designed by Hubbard and McLeod [1974]. [Also, see Hubbard, 1975.] That headform was incorporated without change into the Hybrid III dummy [Foster, et al., 1977; pp 977-981]. The design specifications of Hubbard and McLeod for inertial properties include a mass value of 10.0 lb (4.54 kg) and a moment of inertia I_{yy} about the lateral principal axis of 238 kg-cm^2 ± 10 kg-cm^2 (0.207 in-sec^2-in ± 0.10 in-sec^2-in). The design specifications *do not* include requirements for I_{xx} or I_{zz} or the orientations of their principal axes with respect to an anatomical coordinate system.

The best available inertial property data for the Hybrid III (midsized) headform, as manufactured, are those in the study reported by Kaleps and Whitestone [1988], in which properties of the Hybrid III dummy were experimentally measured. The measured values for mass (9.92 lb) and I_{yy} (240.4 kg-cm^2) are in good agreement with the Hubbard-McLeod design specifications. Clarification is needed, however, in regard to other Kaleps-Whitestone data. Some of the data are *apparently* not in good agreement with the widely cited results of McConville, et al. [1980] [and the same study as reported by Kaleps, et al., 1984], for living male subjects as determined by stereophotometric techniques and multiple regression modeling. While head masses are not greatly different--9.92 lb and 9.632 lb, respectively--the reported values for head principal moments of inertia and the orientation of the principal axes are very different. Kaleps and Whitestone determine their principal X-axis, X_p, to be rotated 26.6 degrees ($\cos^{-1}$ 0.89426) *downward* from the head anatomical reference system (i.e., from the Frankfort plane) while McConville, et al., determine an *upward* rotation of 36.05 degrees--a difference of about 63 degrees. The principal moments of inertia I_{yy} about the lateral principal axis are found to be similar, as shown below, but there is considerable apparent disagreement between the values for the principal X- and Z-axes. In particular, Kaleps and Whitestone report I_{zz} to be much larger than I_{xx} while, conversely, McConville, et al., report I_{xx} to be much larger than I_{zz}. In a personal communication with Dr. Ints Kaleps (October

13, 1994) it was learned that the orientations of the principal axes differ in actuality by about 27 degrees, not 63 degrees, and, further, that the principal moments of inertia are actually in reasonably good agreement since the identifications of X_p and Z_p are transposed in the two studies. Specifically, -$Z_{p,McConville}$ corresponds to $+X_{p,HybIII}$ and $+X_{p,McConville}$ corresponds to $+Z_{p,HybIII}$. Thus, *in terms of McConville's system*, while the human (male) principal X-axis is rotated 36.05 degrees upward from the anatomical X-axis (forward), the Hybrid III "X_p-axis" is rotated 63.4 degrees upward. The Z_p-axes--in terms of McConville's system--are similarly different by about 27 degrees, and both are upward through the back of the crown. In relation to the described transposition of axis definitions, I_{xx} and I_{zz} values in the McConville and Kaleps studies must be interpreted inversely. The two tables below, respectively, show the values of principal moments of inertia as reported in the two studies.

PRINCIPAL MOMENTS OF INERTIA AS REPORTED IN FOR TWO STUDIES	
Kaleps and Whitestone	Ixx = 159.1 kg-cm^2 (0.1408 lb-sec^2-in)
(Hybrid III, midsized)	Iyy = 240.4 kg-cm^2 (0.2128 lb-sec^2-in)
	Izz = 221.0 kg-cm^2 (0.1956 lb-sec^2-in)
McConville, et al.	Ixx = 204.1 kg-cm^2 (0.181 lb-sec^2-in)
(midsized living males)	Iyy = 232.9 kg-cm^2 (0.206 lb-sec^2-in)
	Izz = 150.8 kg-cm^2 (0.133 lb-sec^2-in)

PROPERLY COMPARED PRINCIPAL MOMENT OF INERTIA VALUES FOR THE McCONVILLE AXIS SYSTEM	
Kaleps and Whitestone	Ixx = 221.0 kg-cm^2 (0.1956 lb-sec^2-in)
(Hybrid III, midsized)	Iyy = 240.4 kg-cm^2 (0.2128 lb-sec^2-in)
[transposed values]	Izz = 159.1 kg-cm^2 (0.1408 lb-sec^2-in)
McConville, et al.	Ixx = 204.1 kg-cm^2 (0.181 lb-sec^2-in)
(midsized living males)	Iyy = 232.9 kg-cm^2 (0.206 lb-sec^2-in)
	Izz = 150.8 kg-cm^2 (0.133 lb-sec^2-in)

A review of Appendix A indicates that for some of the major experimental studies in which cadaver head principal moments of inertia are measured, I_{xx} is reported to be much greater than I_{zz} while others show the opposite relative magnitudes. Specifically, Chandler, et al. [1975], and Reynolds, et al. [1975], have $I_{zz} >> I_{xx}$ while Beier, et al. [1980], and Young, et al. [1983], have $I_{xx} >> I_{zz}$, in basic agreement with the values for living male subjects in the McConville study. (Young's values were determined with a regression model from stereophotometric measurements made with living female subjects in the same manner as McConville's for living males.)

Reasons for the relatively large discrepancies between values from different studies for I_{xx} and I_{zz} could not be determined in the present study, except as noted above regarding the seeming, but not actual, discrepancy between Kaleps-Whitestone values for the Hybrid III dummy and the values of McConville, et al., for living human males. Sectioning of cadavers seems to have been done in the same way in the various studies, but small differences in method could have large effect on principal moments of inertia. Further, there is an inherent sensitivity to experimental conditions in the equations for the direction angles of the principal axes that, in fact, increases without bound as the differences between values of the principal moments of inertia approach zero. Additionally, *none* of the authors describe the method used for measuring principal moments of inertia and principal axis orientation--a nontrivial experimental endeavor--so it is not possible to assess the accuracy of reported results. Only the papers of Kaleps and Whitestone [1988] and Kaleps, et al. [1984], include schematics that show the principal axes. (The system used in Kaleps, et al. [1984] is, however, the same as was used for the studies by McConville, et al. [1980], and Young [1983].) Thus, a possible explanation for the two groupings of reported values--$I_{xx} >> I_{zz}$ and $I_{zz} >> I_{xx}$--that seems likely to be correct is that axes are defined oppositely in various studies, as for the Hybrid III and living human male studies described above. If this is true, then if the McConville system is used [see Kaleps, et al. 1984], it would be correct for each study to use the larger of the reported values, I_{xx} and I_{zz}, for I_{xx} and the smaller for I_{zz}. That is, $I_{xx} >> I_{zz}$, where the X_p axis is approximately through the forehead and the Z_p axis is through the back of the crown.

As the (transposed) principal moments of inertia measured by Kaleps and Whitestone for the Hybrid III are in good agreement with the living human male values of McConville, et al., either set of values can be used. For direction angles of the principal axes, however, the McConville value (36 degrees) will be used for the midsized and large headforms and the Young value (42 degrees) will be used for the small ("female") headform. Support for this recommendation is found in the basic agreement between the cadaver measurement results of Beier, et al. [1980] and the results of McConville, et al., in regard to both the reported direction angles (34 degrees and 36 degrees upward) and the reported relative--and absolute--magnitudes of I_{xx} and I_{zz}.

No values for headform volume and average density for the Hybrid III headform could be found in the literature. Consequently, the average density of the Hybrid III headform could not be established. Average specific gravities of cadaver heads, however, are reported by several researchers. These values are included in Appendix A. They range from 1.056 to 1.15. (Specific gravity is called "density" in most of the references.)

5.2 Small and Large Headforms

For small and large headforms, the result of Kaleps and Whitestone for head mass (midsized, 9.92 lb) will be supplemented with the results of Mertz, et al. [1989]. Their values for headforms for the small female and the large male are 8.10 lb and 10.90 lb, respectively. Mertz, et al., while providing values for many properties scaled from midsized ("Hybrid III") to small and large, do not include values for head principal moments of inertia for even the Hybrid III headform. It may easily be shown that, for geometric similarity and uniform and equal density, moment of inertia scales as the 5/3rd power of the ratio of the masses or, equivalently, as the 5th power of the ratio of the lengths. [See Bowman, et al., 1977; pg. 75.] Mertz, et al., give head length-scale ratios relative to the midsized male of 0.931 for small females and 1.030 for large males. The fifth powers of these values are

0.6994 and 1.1593, respectively. These scale factors can be multiplied by the Hybrid III values for principal moments of inertia to obtain the values below. The I_{xx} and I_{zz} values here are the *transposed* Kaleps-Whitestone Hybrid III values, as described earlier.

SCALED HYBRID III HEADFORM	Head Principal Moments of Inertia for the McConville Axis System[1]
Kaleps and Whitestone (transposed values) (Hybrid III, midsized) SCALE FACTOR = 1.0	Ixx = 221.0 kg-cm^2 (0.1956 lb-sec^2-in) Iyy = 240.4 kg-cm^2 (0.2128 lb-sec^2-in) Izz = 159.1 kg-cm^2 (0.1408 lb-sec^2-in)
Scaled Kaleps-Whitestone values (for small female) SCALE FACTOR = 0.6994	Ixx = 154.6 kg-cm^2 (0.1368 lb-sec^2-in) Iyy = 168.1 kg-cm^2 (0.1488 lb-sec^2-in) Izz = 111.3 kg-cm^2 (0.0985 lb-sec^2-in)
Scaled Kaleps-Whitestone values (for large male) SCALE FACTOR = 1.1593	Ixx = 256.2 kg-cm^2 (0.2268 lb-sec^2-in) Iyy = 278.7 kg-cm^2 (0.2467 lb-sec^2-in) Izz = 184.4 kg-cm^2 (0.1632 lb-sec^2-in)

[1]The Xp axis is approximately through the forehead and the Zp axis is through the back of the crown.

5.3 Definitions and Other Considerations

All researchers whose data are presented in Appendix A used essentially the same *anatomical coordinate system* for the head. The definition of Kaleps and Whitestone [1988] is as follows: The Y-axis unit vector *Y* is from right tragion to left tragion. The X-axis unit vector *X* is parallel to a vector that is normal to the Y-axis and passes through right infraorbitale. The X-axis itself passes through the midpoint between right and left tragion, and the Z-axis unit vector is *X* x *Y* (upward). *X* and *Y*--or, equivalently, the three points right tragion, left tragion, and right infraorbitale--define the "Frankfort Plane." (The head anatomical coordinate system is sometimes called "Frankfort Horizontal.") Differences between this definition and ones used by other researchers are negligible in regard to use of data from Appendix A. Those differences include: (1) use of right and left auditory meatus instead of right and left tragion for the *Y* vector; (2) definition of *X* as a normal to *Y* that passes through nasion (sellion).

Two additional points regarding the cadaver data in Appendix A need to be made. First, no female cadavers were included in any of the studies done with cadavers. Further, no study identifies data from male cadavers as being for "small," "midsized," or "large" males (or heads). That is, average values presented by the authors are from cadaver pools in which small, midsized, and large heads are all included. It is, therefore, almost a necessity that an assumption be made that "midsized" can be equated with "average." Any other definition would reduce already small sample sizes to an extent that results would have greatly reduced statistical significance.

6.0 LOCATIONS OF THE HEAD CENTER OF GRAVITY AND THE OCCIPITAL CONDYLES PIVOT

Locating the head center of gravity (CG) properly for the small, midsized, and large headforms is important for dynamics studies, including helmet retention studies. In order that the head of the manikin be able to replicate human response reasonably well, this means that its CG location with respect to the head-neck pivot should be reasonably accurate. For static fit studies the location of neither the CG, nor the head-neck pivot, is of significance.

Numerous references have been found that contain data pertinent to properly locating the head center of gravity and the occipital pivot in the headforms designed in the present study. Those data are given in Appendix A. The references in Appendix A begin with ones pertinent to the Hybrid III dummy headform, and references for cadaver studies, or studies in which cadaver data were used, follow. As for inertial properties, Hybrid III headform data for the center of gravity and the occipital pivot will be used for the midsized headform designed in the present study. Here, as for inertial properties, the data presented from cadaver studies are the very data that were used, collectively, to establish and corroborate the design of the current Hybrid III headform. A reanalysis of the available cadaver data would not produce results for the locations of the CG or the occipital condyles that are significantly different from the values adopted for the Hybrid III headform.

In nearly all listed references the same anatomical coordinate system defined previously was used, viz., one in which *X* and *Y* define the Frankfort plane and *Z* is normal to the Frankfort plane at the midpoint of the Y-axis between right and left tragion.

The center of gravity of the head is assumed, or measured, to be on the midsagittal plane--i.e., at Y=0--by all researchers. Nonzero Y_{CG}, whenever measured, is small enough to be negligible. The coordinates of the CG are in nearly every instance given relative to the origin of the anatomical coordinate system. The most common exception to this is identification of the X and Z separations between the CG and the occipital condyles (along the anatomical X- and Z-axes) without accompanying values that locate either the CG or the occipital condyles with respect to the anatomical coordinate system.

The occipital condyles location has been selected as the best for the head-neck pivot for headforms designed in the present study. This is in accordance with the design of the Hybrid III headform. There are two occipital condyles in the human head, separated symmetrically to the left and right of the midsagittal plane. As there is essentially no lateral articulation at this "joint," however--i.e., only pivoting in the midsagittal plane--it is unnecessary to determine Y coordinates for the occipital condyles. Rather, only the X and Z coordinates of the axis of rotation at the occipital condyles need be established. The occipital condyles (and the CG) can be located with respect to any point on the head if the coordinates of that point and the coordinates of the condyles are both known with respect to the anatomical coordinate system (which can be defined absolutely if the laboratory frame (X,Y,Z) coordinates of left and right tragion and right infraorbitale are known).

6.1 Midsized Headform

The design of the Hybrid III headform--originally developed for the GM ATD 502 crash dummy--locates the CG and the head-neck ("occipital condyles") pivot relative to each other and relative to head and face landmarks. [See Appendix A: Hubbard and McLeod, 1974; Hubbard, 1975.] In the anatomical (Frankfort Plane) coordinate system the CG is 1.9 inches above and 0.7 inches forward from the occipital condyles.

There is good agreement between the various authors in regard to the relative locations of the CG and the head-neck pivot in the actual Hybrid III (midsized) headform. In the head anatomical coordinate system the CG is 2.00 inches above and 0.55 inches forward from the head-neck pivot according to Kaleps and Whitestone [1988], Spittle, et al. [1992], and Grewal, et al. [1994]. These values are *not* in agreement with the design specifications of Hubbard and McLeod. Denton and Morgan [1988] give a value of 1.9 inches for the superior-inferior (Z) separation and a value of 0.7 inches for the anterior-posterior (X) separation. Either of these two sets of values is suitable for the midsized headform.

All values for midsized males tabulated in Mertz, et al. [1989] are identified as being for the Hybrid III dummy. However, these values are, in fact, all taken from cadaver studies and therefore represent midsized males rather than the actual Hybrid III dummy. Mertz, et al., give a value of 1.9 inches for the superior-inferior separation between the head CG and the occipital condyles--viz., the *design* value of Hubbard and McLeod. Mertz, et al., do not give a value for the anterior-posterior separation, but the Hubbard-McLeod specification for the anterior-posterior separation is 0.7 inches.

6.2 Small and Large Headforms

If the Mertz (Hubbard-McLeod) values are used for the midsized headform and if the anterior-posterior separation is scaled in the same manner that Mertz, et al., scale the superior-inferior separation between CG and occipital condyles--viz., on the basis of characteristic dimensions for the skull--the values below are obtained for small females and large males. The Mertz head-dimension scale factors for the large male and small female are 1.030 and 0.931, respectively.

CADAVER DATA (SCALED)	CG to Occipital Superior-Inferior	Condyles Separation Anterior-Posterior
Mertz/Hubbard & McLeod (midsized male, "Hybrid III") SCALE FACTOR = 1.0	1.9 in	0.7 in
Mertz/Hubbard & McLeod (small female) SCALE FACTOR = 0.931	1.8 in	0.65 in
Mertz/Hubbard & McLeod (large male) SCALE FACTOR = 1.030	2.0 in	0.72 in

If the Hybrid III values, 2.0 inches and 0.55 inches, are used instead of the cadaver-based design values (1.9 inches and 0.7 inches), similar scaling would be reasonable. The results, shown below, are not greatly different from those above from scaling of midsized-male cadaver data.

HYBRID III DATA (SCALED)	CG to Occipital Superior-Inferior	Condyles Separation Anterior-Posterior
Hybrid III (midsized male) SCALE FACTOR = 1.0	2.0 in	0.55 in
Small female (using Mertz scale factor) SCALE FACTOR = 0.931	1.9 in	0.51 in
Large male (using Mertz scale factor) SCALE FACTOR = 1.030	2.1 in	0.57 in

7.0 SKIN PROPERTIES

The literature search did not disclose much useful data for skin properties of the human head. Specifically, it has not been possible to determine the friction properties of the scalp, with or without hair, and, further, it has not been possible to establish force-deflection properties of the face and scalp as a function of position on the head. (Frangible face forms are not relevant to the present study.) Information is available, however, for the thickness and composition of skin on the Hybrid III headform. The headform skin specifications for the Hybrid III were established to meet requirements of durability and proper head-acceleration response in drop tests with impact to the forehead. The Hybrid III headform skin will be considered for headforms developed in the present study.

7.1 Friction Properties

The scalp is described [Prasad, 1988] to be 5 to 7 mm (0.20 to 0.28 in) thick including the hair-bearing skin and the layered soft tissues between the skin and the skull. All of the layers of the scalp move together as one. Also, a loose connective tissue layer plus a fibrous membrane cover the bone (periosteum).

Prasad, et al., note the looseness of the scalp on the skull. Neither they nor (apparently) any other researchers have attempted to quantify this looseness. Also, no measure of the friction between the scalp's hair, or the skin of the face, and any contacting surface is given. Neither these authors nor any others quantify the force-deflection characteristics of the scalp (except in the form of constitutive properties, e.g., McElhaney, et al., 1969, and Melvin and Evans, 1971).

Webster and Newman [1976; pp. 233-235] describe qualitative properties, however; viz., that surface friction should be *small* and the coupling of the scalp to the cast aluminum skull of the headform should be *weak*. In a comparison of force-time history responses for impacts to cadaver heads and anthropomorphic headforms, they found that the headform force responses that most nearly replicated cadaver head force responses were for headforms with smooth, low-friction "skin" surfaces and skin that is not fastened to the skull--i.e., skin that is free to slide over the headform surface. Hodgson [1990] also conducted friction (skid) tests for anthropomorphic headforms, but did not include cadaver tests in his study.

The apparent absence of quantitative data for the friction properties of the scalp, and hair, is probably not serious provided that the guidelines of Webster and Newman are followed. Adequate representation of human hair friction characteristics in manikin headforms is probably most important for helmet retention tests. However, proper helmet fit and the design and fit of retention straps are much more important factors than friction between the helmet and the hair. Even if quantitative data for hair friction properties could be found, it would then still be necessary to design the headform scalps in such a way as to replicate these properties. Probably the only ways to accomplish this would be (1) to use a headform covering that has numerous hair plugs or else to put a wig made from human hair, or a suitable substitute, over the headform covering, or

(2) to use a smooth, relative slick headform covering. The latter method is clearly easier, but it requires further study.

7.2 Force-Deflection Properties

Head force-deflection properties may be important for impact studies with Army manikins (or the headforms and necks alone), but the importance in impact studies relevant to helmeted personnel would certainly be much less than in studies for which no helmet is present. Since studies in which impacts of the unhelmeted Army headforms occur are unlikely to be of interest, it is probably not important to have more humanlike head force-deflection properties than in the Hybrid III. In any case, no force-deflection specifications more representative of a human than those for the Hybrid III headform were determined in the present study.

Early work done by Thurlow [1963] established that the shock-absorption properties of the living human scalp may be simulated in anthropomorphic dummies by covering the heads with a 5/32-inch thick layer of cellular silicone rubber. Research conducted since Thurlow's work has determined the best formulation for the skin to be ARL Vinyl Formulation No. PT-4. This is used for the current Hybrid III headform [Howe, et al., 1991; Benson, et al., 1991]. Skin thickness for the Hybrid III varies at positions over the face. It is 1.55 cm at nasion, 1.09 cm at zygoma, and 1.13 cm at maxilla [Gallup, et al., 1988; pg. 332]. Gallup, et al. (ibid), recommend 1.00 cm at nasion, 1.10 cm at zygoma, 1.10 at maxilla, 1.05 cm at subnasale, and 1.10 for the nose. Corresponding specifications for the Hybrid III 5th percent female and 95th percent male crash dummies were not found in the present study, but it may well be that they should be different from the 50th percent dummy specifications in order to satisfy drop-test acceleration requirements.

Only very limited head force-deflection data [except for frangible faces: Newman and Gallup, 1984; Allsop, 1993] is available for even the Hybrid III dummy, which is used routinely for impact studies involving automobile occupants, which are unhelmeted. In particular, the forehead covering of the Hybrid III headform is of such composition and stiffness as to allow replication of head acceleration responses in cadaver head (forehead) drop tests. Possibly the first work on cadaver head drop tests was done by Hodgson and Thomas [1972]. Prasad, et al. [ibid; pp. 12-13], report results derived from the work of Hodgson and Thomas, and they find, specifically, that the peak acceleration of the center of gravity of the head should be within a corridor defined by corner points of 230 ± 42 G for free-fall drops of 330 mm and 293 ± 42 G for drops of 1060 mm. The headform and headform covering of the Hybrid III dummy satisfy these test criteria.

Mertz, et al. [1989] scaled the response range to obtain values appropriate for "small female" and "large male" headforms. Dividing the Hybrid III acceleration values by a scale factor of 1.030 for "large male" and 0.931 for "small female" and rounding to the nearest 5 G, they obtain lower limit, midpoint, and upper limit values, for drop heights of 14.8 inches, as follows: large male - 220 G, 245 G, and 265 G; small female - 240 G, 270 G, and 295 G.

Two final observations regarding force-deflection properties of the head are made here. First, Hodgson and Thomas [1971] state that impact force for direct impacts to the heads of bushy-haired individuals can be distributed sufficiently to raise the fracture force level by a significant amount. This would not be a factor for impacts to the helmeted manikin headforms. Secondly, Sakurai, et al. [1993], have demonstrated in headform impact tests, with and without skin, that the influence of headform skin on the maximum acceleration and the HIC value is insignificant, although the presence of the headskin does serve as a low-pass filter on high-frequency elements.

8.0 HEADFORM MODEL DEVELOPMENT

The headform models were developed using a computer-aided design package from Autodesk, Inc. of Sausalito, CA. AutoCAD Release 12 was used in conjunction with the AutoSurf Release 2 surface modeling system to generate the complex splines and surfaces that compose the computer models of the headforms. The AutoCAD software package was chosen for this design task after consideration of its popularity, flexibility, and integrated surface modeling features.

Initially, a medium sized headform was created using anthropometric data corresponding to a 50th percent male from a U.S. Army Natick technical report [Gordon, 1989]. Construction of this headform proceeded with the definition of the headform skin surface first, and later involved the generation of the headform skull surface. The 48 headboard measurements yielded the location of 26 facial landmarks which were transformed into three-dimensional coordinate data. Three orthogonal coordinate axes were drawn in space and their intersection was defined as the origin of the local coordinate system. Data points were entered in reference to this local origin, and the XY and YZ planes of this coordinate system were considered the headboard reference. Head symmetry about the mid-sagittal plane was assumed in the construction of the headform.

The wireframe of the medium headform is pictured in figure 3. The wireframe was started by creating a satisfactory head/facial outline along the mid-sagittal plane. A spline fit was created from the crinion to the menton, and passed through the six other intermediate facial landmarks that lie on the mid-sagittal plane. This outline was supplemented by additional control points as needed to obtain an adequate facial profile. The 26 facial landmarks are circled in figure 4 to illustrate their position in relation to the wireframe construction. The head outline was constructed from two spline curves that were drawn to selected contact points on the horizontal and vertical sections of the headboard. These contact points were approximated in relation to the location of known landmarks and the alignment of the head. The head outline extended down until the level of the frontotemporale landmarks. Both the head and facial outlines were extended down to form the neck until a plane was reached ten inches below the top of the head. This was judged to be adequate for the headform neck representation.

The width of the head was constructed from a spline fit between the tragion landmark and the top of the head. Additional points used in the construction of this curve were deduced from measurements pertaining to the maximum head breadth. Construction features were generally created on the right side of the headform and then mirrored across the mid-sagittal plane for symmetry. The mirroring technique reduces the overall model construction time, ensures symmetry across the mid-sagittal plane, and provides proper mating between

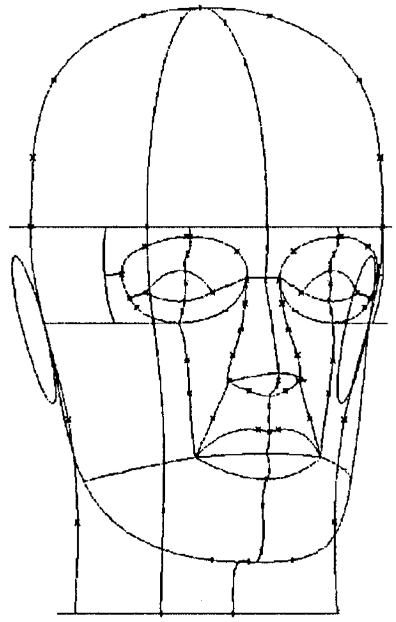


Figure 3. Headform Skin Wireframe

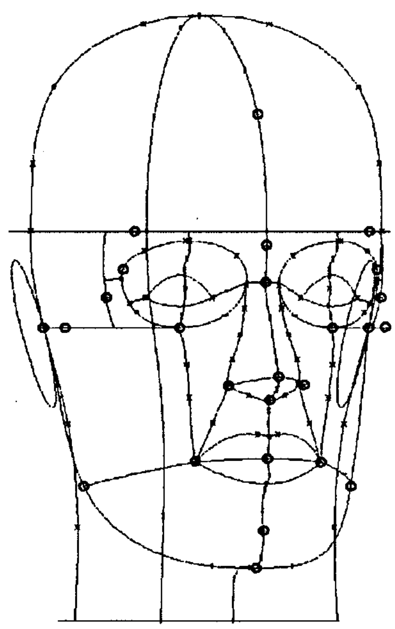


Figure 4. Headform Skin Wireframe with Landmark Indentification

adjoining sections of the headform. The neck width was created by constructing a circle with a diameter calculated from the neck circumference measurement. This circular cross-section would later be blended as a surface to the adjoining regions of the head and face. The jaw line was created as a spline fit through the menton, gonion, and tragion. Additional control points were added to achieve a satisfactory mandibular profile. The facial wireframe was created by relating the zygion, cheilion, alare, ectoorbitale, infraorbitale, and zygofrontale landmarks to the mandibular profile and mid-sagittal plane. Construction splines were created at positions which were proximate to the available facial landmarks, and at positions which characterize a natural point of inflection in the facial curvature. The position of the eyes was determined from the interpupillary breadth measurement and the position of the facial landmarks located around the perimeter of the eye socket. The ears were created as ellipses that were slightly rotated about the tragion landmark. The dimensions of the major and minor axes of the ellipse were decided from the ear length and ear breadth measurements, respectively.

Surface modeling of the headform proceeded during the wireframe construction process as the regions were completed to satisfaction. The headform surfaces were represented using NURBS (Non-Uniform Rational B-Spline) mathematics within the AutoSurf modeling environment. The surfaces were generally created as swept sections of mesh between closed portions of the wireframe. Generation of the surfaces was necessary during the construction of the wireframe to effectively visualize the resulting curvatures. Mesh with a greater density was used in regions with more complex surface curvatures. The headform surface mesh layer is shown in figure 5. This surface mesh can then be transformed into polygon faces that are able to be rendered by the AutoCAD rendering tools. Rendering of the model is accomplished by variable levels of shading that are related to the angle of each polygon face. Polygon faces that are nearly perpendicular to the plane of view are the brightest, while faces that are at an angle away from the plane of view appear darker. The rendering process allows an accurate inspection of the finished surface curvatures, and may reveal discontinuities in the surface model or misalignment between neighboring surface regions. A rendered image of the headform surface is pictured in figure 6.

Considerable effort was expended in attempt to smooth the transition between adjoining facial surfaces. Wireframe splines that were created acted as boundaries between neighboring surface regions. Attempts to join neighboring surfaces into a larger, continuous surface sometimes produced unpredictable results and resulted in a decrease in design flexibility. However, the joining of neighboring surfaces was effective in reducing the shading discontinuities between facial regions. Best rendering results were obtained when the surface display tolerance was reduced to its lowest allowable level. A substantial increase in rendering time comes as a result of the reduced polyface mesh tolerance.

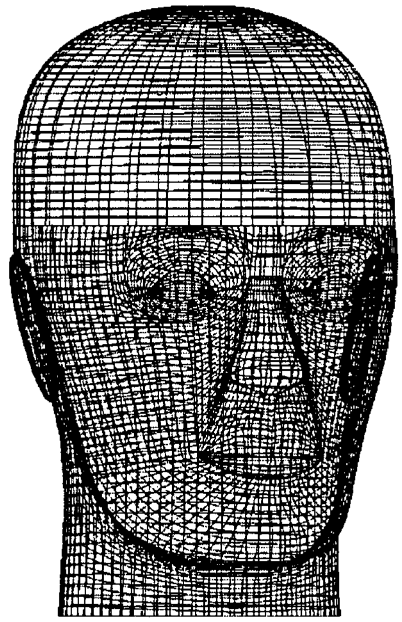


Figure 5. Headform Skin Surface Mesh

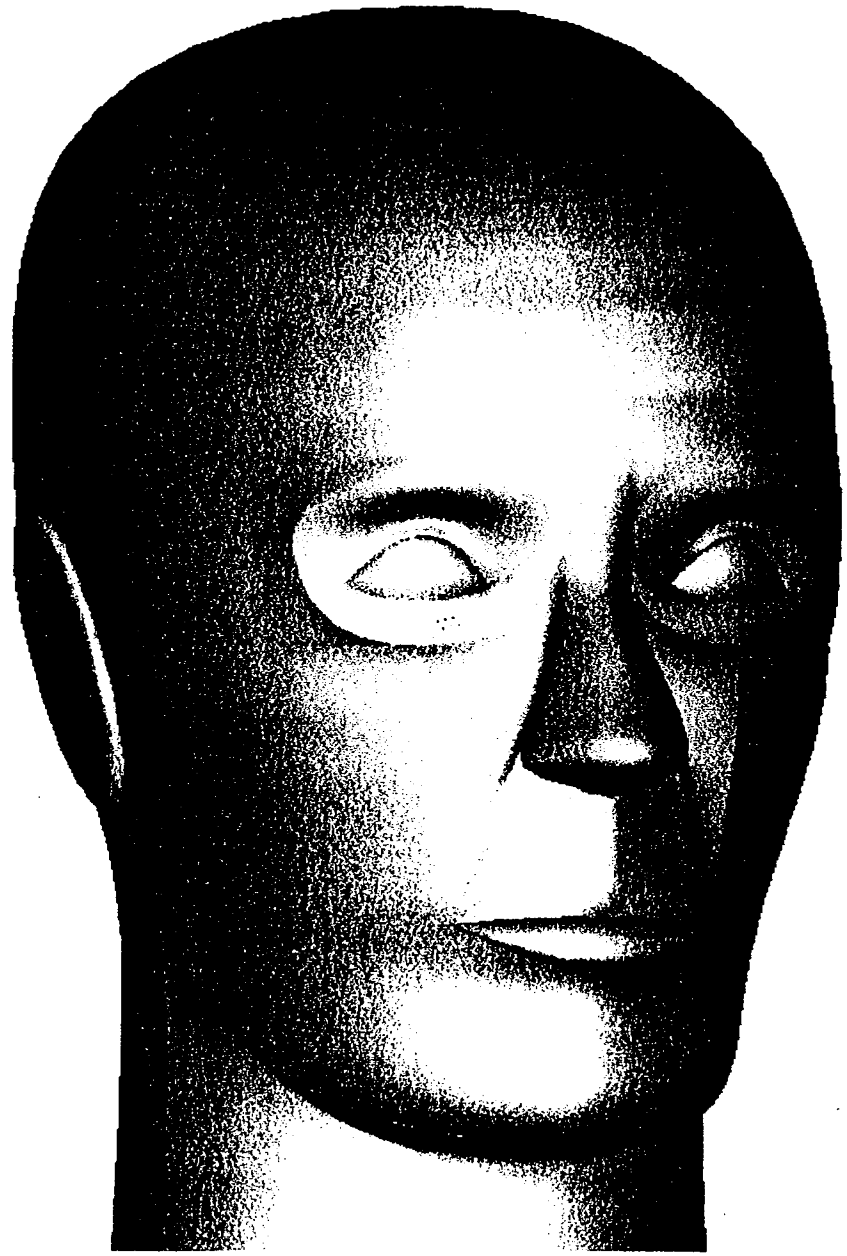


Figure 6. Headform Skin Surface Rendering

The surfaces of the medium headform skin model were constructed between splines that were drawn through the landmark points. Therefore, agreement of this model with the 48 linear headboard measurements has been confirmed. Accurate measurement of the various head arcs and circumferences has not yet been accomplished, and agreement of these measurements with the anthropometric data has thus not been confirmed. It is expected that agreement with the anthropometric head arc data will be the most difficult to achieve because the headform surfaces are approximated by intermediate points between the known landmarks in these locations. A level of surface control point editing and trial and error may be necessary to achieve a anthropometrically perfect headform model on the computer.

The medium headform skull model was developed from the medium headform skin model. The skull surface was generated as a reduced scale copy of the headform skin, and was modified to represent the shape of a human skull. The size of the skull relative to the exterior skin surface will result in uniform skin thickness over the skull surface that is consistent with the Hybrid III headform. This skin thickness (0.441±.031 in.) [General Motors, 1978] has been found to provide acceptable biofidelic response of the Hybrid III headform when covering a rigid aluminum skull. The headform skin layer also extends down to form a neckline over the skull model to provide an improved helmet chin strap interface over the Hybrid III headform. The skull design features a curved front surface with slight surface depressions that represent the eye sockets. A rendering of the skull surface is shown in figure 7. Although at the time of this report only the outer surface of the skull has been defined, consideration has been given to the internal details that will facilitate correct mounting of the head load cell and neck assembly. The current Hybrid III mounting arrangement will be utilized to maintain the Denton six-axis load cell and Hybrid III neck mounting capability. Positioning of the head center of gravity and occipital condyles pivot in relation to the tragion landmarks has also been addressed. For the medium headform model, the head center of gravity will be located 0.41 in. forward and 1.05 in. above (+0.41,+1.05) the tragion landmark. The occipital condyles pivot location will be located 0.29 in. behind and 0.85 in. below (-0.29,-0.85) the tragion landmark. These locations were derived from data obtained from two manikin headform reports [Mertz, 1989], [Hubbard, 1974]. The occipital condyles pivot location will be the pinned connection point between the Denton neck load cell and the Hybrid III neck assembly.

Generation of the small and large sized headforms was accomplished through the non-uniform scaling of the medium sized headform about the three coordinate axes. The scaling values for each direction were determined through a comparison of the head dimensions found for the small and large sized headforms with the dimensions of the existing medium headform. A ratio that related either the small or large headform value to the medium value was formed for each head dimension, and this yielded a sizing multiplier for each dimension. Of the 48

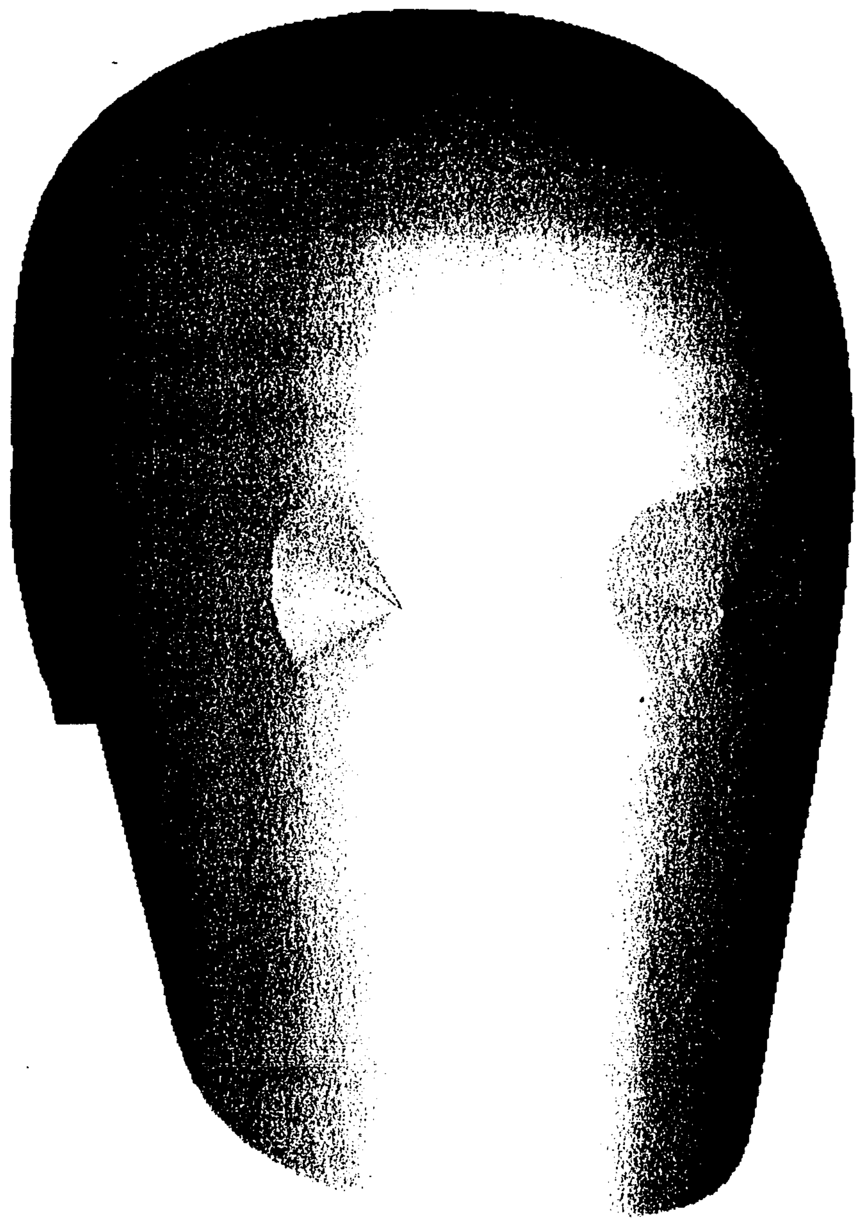


Figure 7. Headform Skull Surface Rendering

headboard measurements tabulated for the three sizes of headforms, 17 measurements are oriented in the X and Z directions, and 9 measurements are oriented in the Y direction. The 5 remaining headboard measurements are not parallel to either the X, Y, or Z axes and were not used in the size comparison. The sizing multipliers for the headboard measurements were summed in each of the three coordinate directions and then a separate average sizing multiplier was calculated for the X, Y, and Z directions. The average sizing multipliers and the standard deviations found in each direction are presented in Table 7.

Table 7. Headform Sizing Multipliers

	Xave	**Yave**	**Zave**	**Xdev**	**Ydev**	**Zdev**
Small	0.948	0.948	0.932	0.017	0.026	0.019
Large	1.046	1.043	1.035	0.012	0.019	0.027

These three average sizing multipliers were used as the coordinate scale factors to deform the medium sized headform to fit the small and large headform anthropometric data. The headform deformation was accomplished through the non-uniform scaling of the medium headform design about a point in the center of the headform that was determined by the location of the tragion landmark. Thus, the small and large headforms resulted from variable reduction or expansion of the medium headform based upon the comparison of the statistically determined headform dimensions. The small and large headform skin surfaces fit the plotted landmark points adequately, but do not pass directly through the individual facial landmarks. This is supported by the calculation of the standard deviation in each coordinate direction which did not exceed 3 % for either headform. For all of the headform surfaces to pass directly through the landmark points, each headform wireframe must be constructed from the designated landmark points. The surfaces that are created between sections of the wireframe can be joined to yield a final headform skin surface that passes through each facial landmark. Separate construction of each of the three headforms using their landmark points was not possible due to project time limitations, but this method would produce the best agreement between the actual headform model dimensions and the tabulated anthropometric data. Positions of the center of gravity and occipital condyles pivot for the small and large sized headforms will be determined from studies that were revealed in the UMTRI literature search.

It should be noted that the dimensions of a medium headform that were revealed by the multivariate limit analysis were not used in the determination of the facial landmark positions of the medium headform model. These facial landmarks were located from head dimensions reported for a 50th percent male [Gordon, 1989]. However, the subsequent comparison of the multivariate medium dimensions with the 50th percent male dimensions showed that they are very similar.

The exterior surfaces of the headform skin and skull are described using waterlines and a headform coordinate system. Figure 8 illustrates the position of the headform sections or waterlines. The sections are located every inch away from the Frankfort plane in both directions, and at the bottom opening of the skin or skull layer. A headform coordinate system is constructed at the reference plane with its origin located at the center of the head, at the midpoint of a line passing through the tragion landmarks on opposite sides of the head. A depiction of the headform coordinate system is shown in figure 9. Tabulated data for the small, medium, and large headform skin and skull surfaces is included in Appendix ?. One side of each section is described parametrically at increments of ten degrees in Cartesian and polar coordinates. Each headform is symmetrical about the mid-sagittal plane. The apex point is located at the center of the circular hole in the top of the skin or skull layer which allows the lifting ring to thread into the skull.

The AutoCAD software can produce output files that accurately describe the headform surfaces in the Initial Graphics Exchange Specification (IGES) format. The IGES format was developed as a standard for the exchange of drawing information between CAD systems, and can be used effectively in the fabrication and machining of solid models from computer generated designs. Accordingly, the headform computer design model can be copied to floppy disks or a data cartridge in the IGES format and a solid model could be fabricated by a machine shop which has IGES conversion capabilities. This provides a convenient and reliable method of producing solid models of the headforms upon demand.

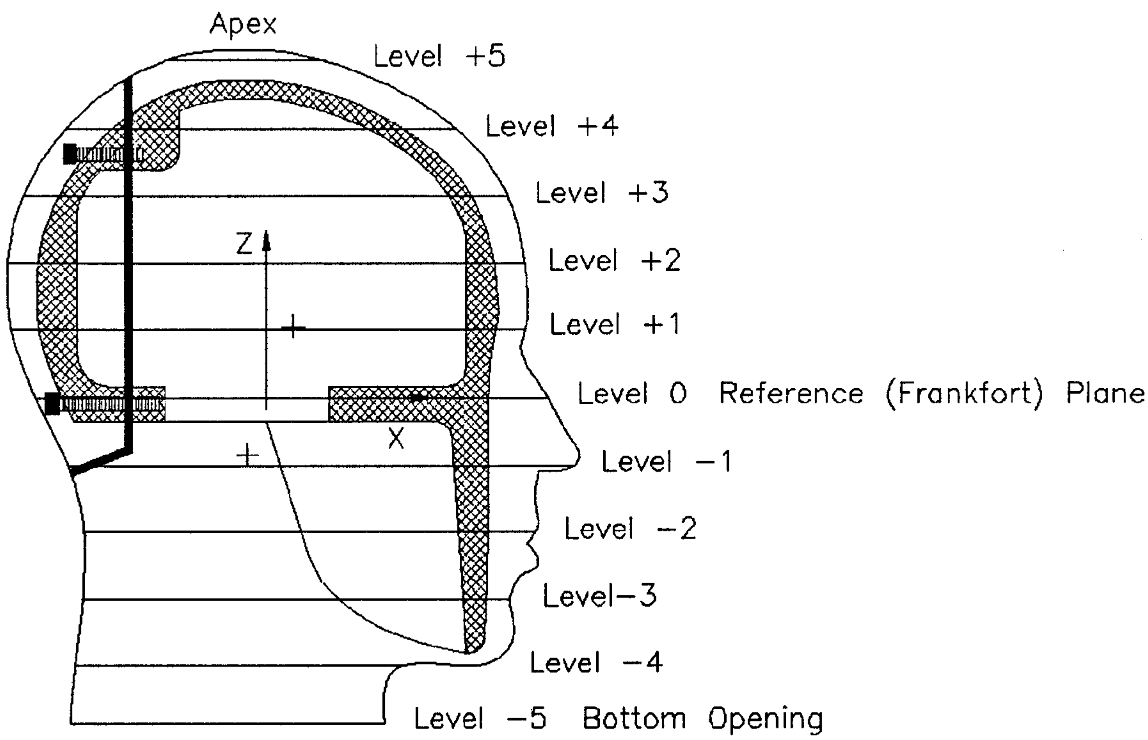


Figure 8. Headform Sections - Mid-Sagittal Plane

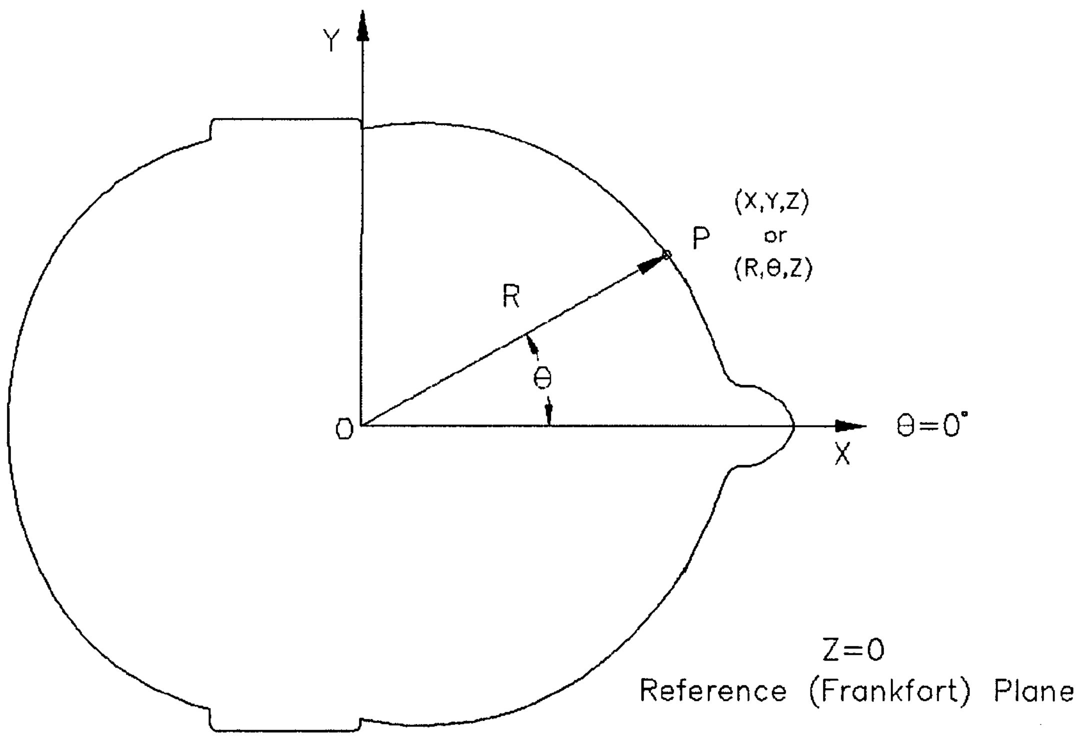


Figure 9. Headform Coordinate System

9.0 HEADFORM FABRICATION ALTERNATIVES

The Phase I program for the development of anthropometric analogous headforms includes headform design and material selection. Fabrication, or the specification of fabrication procedures, recognized as an essential aspect of the development of usable headforms, is not included in Phase I. Conrad Technologies, Inc. (CTI), however, does have experience in the fabrication of manikin components and is cognizant of the various fabrication procedures that are available. To accomplish fabrication, the transferral of the computer-generated surfaces of the design into either a mold, a physical model or a prototype is a key step in the fabrication process. Several current fabrication technologies which are pertinent to the construction of the headform models have been explored.

There are many procedures that are available to transfer a computer-generated surface of an object, such as the headform, into an actual physical embodiment having the same surface profiles as the computer model. In general, there are two classifications of fabricating procedures. The first classification being the more conventional techniques of programming a machine to remove unwanted material from a block of material and thus, shaping the machined model. The second classification being procedures that build a model or prototype by adding or building up thin layers of material in accordance with the corresponding section of the computer-generated surfaces.

The material removal techniques require the programming of the tool path of the cutter and in some cases requires specialized tooling. Tool path programs are available to transfer the computer-generated surface into actual paths of the cutting tool. In cases where the product requires processing or curing at an elevated temperature in the mold, machining of the mold out of aluminum or steel may be a requirement.

The material build-up procedures normally utilized a laser or high-intensity light source in order to contour sections within the model and to successively contour sections on top of one another in order to build up a model or prototype. There are four laser fabricating procedures described below.

9.1 Stereolithography

Stereolithography is a commercial process utilizing a UV laser to cure thin sections of a photosensitive polymer. The laser traces and cures individual cross-sectional elements (about 0.1 mm thick) of the prototype. A platform is positioned in a bath of photosensitive polymer at 0.1 mm below the surface of the polymer and the laser is then made to trace and cure the first 0.1 mm thick section. The platform is then proved a small distance further into the bath (approximately 0.1 mm) and the laser traces and cures a second layer of material on top of the first. Successive layers are traced and cured until the model is complete. Scan speeds may be as high as 350 in./sec. thus allowing rather rapid prototyping. Current photopolymers have good dimensional accuracy and toughness although some care is required in selecting process parameters. Scans are driven by CAD software files with stereolithography "STL" filename extensions.

9.2 Selective Laser Sintering

Selective Laser Sintering (SLS) is a process that fuses powdered material into rigid solids. In selective laser sintering, prototype parts are produced by fusing successive thin layers of a fusible powder onto the previous layer in order to build up the model. A CO laser is used to scan and heat a selective region with powder being present and causing the powder to melt and fuse in the desired location and providing a build-up of the model.

9.3 Directed Light Fabrication

Directed light fabrication (DLF) is a process in which metal powders are projected at the focal point of a Nd:YAG laser causing the metal powder to fuse and by selectively fusing additional material allows the building of dense 3-D objects to within a few thousands of an inch of the final tolerance. Most any metal, including 300 and 400 series stainless steel, tungsten, nickel aluminies and molybdenum disilicide, copper and aluminum, can be used to fabricate a part.

9.4 Laminated Object Manufacturing

Laminated object manufacturing is accomplished by utilizing a laser to trace and cut out cross-sectional layers from a thin sheet of material such as foil, paper or plastic. These thin sections are then assembled one on top of another to form the model or prototype.

10.0 CONCLUSIONS

The completion of Phase I has resulted in several key points of interest concerning headform design.

The methodology used for characterizing extremes of population in the anthropometric study was different than conventional multivariate analysis methods. Methods such as the bivariate normal distribution model [Churchill, 1978] and principal components analysis [Zehner, 1992] presume a normal population distribution and require a degree of judgment to obtain design limits. The multivariate limit analysis that was used in this project leads to the design limits directly.

The multivariate limit analysis led to the calculation of average probability densities during the iterative algorithm. The maximum average probability density identifies the size of a single headform that would best represent the measured population. The maximum average probability density was found at a point which corresponds to the following values for the independent variables of method 1.

Head Length(mm)	Head Breadth(mm)	Head Circumference(mm)	Menton-Sellion(mm)
195.20	149.50	557.15	121.50

Comparison of the headform dimensions revealed from the multivariate limit analysis with the dimensions of the Hybrid III family has produced some interesting conclusions. All multivariate limit analysis results were found from the ANSUR database which included both male and female military subjects. The Hybrid III family was developed by the Department of Transportation and the headforms were designed from exclusively male or exclusively female civilian anthropometric data. The three headform dimensions that are commonly used in relative size comparison are head circumference, head breadth, and head length. Values of these key parameters for a small adult female, 50th percentile male Hybrid III, and large adult male are compared to the corresponding values obtained from the multivariate limit analysis in Table 8.

Table 8. Comparison of Hybrid III Headform Dimensions with Multivariate Analysis Results using Method 1.

	Hybrid III Small Adult Female	Multivariate Analysis Small	Hybrid III 50th %tile Male	Multivariate Analysis Medium	Hybrid III Large Adult Male	Multivariate Analysis Large
Length	7.20	7.32	7.75	7.69	7.95	8.30
Breadth	5.71	5.60	6.06	5.98	6.14	6.35
Circumference	21.00	21.19	22.60	22.19	23.40	23.44

Note: (All dimensions are given in inches.)

In general, the sizes of the headforms that were produced by the multivariate limit analysis are larger than the Hybrid III family of headforms. However, the medium multivariate dimensions are slightly smaller than the 50th percentile male Hybrid III. This could have resulted from the inclusion of female subjects in the ANSUR anthropometric survey, which compose approximately a quarter of the subjects selected for the medium sized headform. Additionally, the multivariate analysis was performed on the ANSUR survey data which was acquired from 1987-1988, while the Hybrid III sizing was performed during the early 1970's. The more recent ANSUR data source may be more representative of the current population, and the development of the Automated Headboard Device may have provided more accurate measurement of head and face features.

Improvements upon the biofidelity and durability of the current Hybrid III headform has also been addressed. The extension of the headform skin layer down to the neck level provides an improved helmet chin strap interface, and reduces the stress concentrations and skin deterioration found in the chin region. Alternative headform mounting and access concepts have been presented in the Phase II proposal. These concepts aim to eliminate the skin discontinuity that is caused by the access cover of the Hybrid III headform, provide greater access to the enclosed test instrumentation, and simplify the task of connecting the headform to the Hybrid III neck assembly.

The ANSUR anthropometric data used in the Phase I analysis can be considered superior to other anthropometric data sources for headform design because of its facial landmark data. The location of 26 landmarks allow for the accurate facial representation on each of the headforms, and facial detail has been proven to be useful in fit and retention assessment of goggles, masks, and other face mounted systems. Other headform designs do not locate the center of the pupil, or are deficient in eye, nose, and mouth detail.

Information learned from the literature search has also revealed that the headform skin properties are the most important factors in determining the head impact response. The thickness and material properties of the current Hybrid III skin specification have been selected to also be the skin specification for the Phase I headform specification. However, different applications of the headform may require the need for variable skin thickness and properties, and an additional review of skin flesh requirements is needed.

Future work recommendations:

- The multivariate analysis developed during this effort shows the promise of more general applicability. Several avenues of research pertaining to equipment, workspace and protective gear design remain unexplored. Continuing effort in extending the analysis is highly desirable. For example, a variation on the multivariate limit analysis would be to compute a product of independent variables for each subject and then divide the subjects into three groups (small, medium, large) based on their products. Using the multivariate limit analysis method, it would then be possible to determine the headform measurements by maximizing the average probability density of each group.

- Review the selection of headform sizes developed in this program and finalize the anthropometric and biomechanical specifications for these headform sizes. The specifications will be reviewed for proper representation of sample population, complete definition of headform requirements, biofidelic adequacy, testing requirements, performance standards, fabrication requirements and adequacy.

- Review and finalize skull and headform surfaces developed during this phase as required to satisfy the aforementioned specifications.

- Using the finalized headform surface, fabricate full scale prototypes of the surfaces for subsequent inspection and evaluation. This inspection provides an opportunity to determine if the computer generated files for the surfaces and the fabrication techniques provide adequate results in accordance with the aforementioned specifications. In addition, it provides the opportunity for an overall visual inspection of the surfaces.

- Review design concepts developed to improve the assembly, access, fabrication, and related design attributes of the headform while retaining all anthropometric and biomechanical requirements. Based on this review, revise and/or develop alternative design concepts.

- Once a final design concept is selected and shown to meet all specifications such as total mass, mass distribution, impact strength, and structural dynamics, the fabrication and testing of the headforms can be initiated.

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APPENDIX A

LITERATURE SEARCH

LIST OF TABLES

LITERATURE SEARCH

A literature search intended to help establish the most appropriate design specifications for headform characteristics and properties was conducted in a continuing manner over the course of the project. References of potential interest were those that have pertinence to anthropometric modeling, head anthropometry, inertial properties, skin and surface properties, and location of the center of gravity and occipital condyles. Over 500 references were identified on the basis of keyword, author, corporate author, and title searches as being of potential usefulness; these were obtained and examined. A large proportion of those references were identified by keyword searches. Searches for keywords within titles of articles and in keyword fields were conducted. Keywords (and stems), sometimes used in logical 'and' combinations, included: manikin, dummy, head, headform, face, facial, neck, force, load, friction, helmet, mask, goggle, fit, strap, retention, nape, chin, skull, dura, skin, scalp, hair, cranial, anthropom, Hybrid III, Hybrid 3, AATD, ATD, inertia, mass, 3-D, 3-dimensional, surface, contour, and others.

Approximately half of all identified references were found to be of no interest upon perusal. Additional references were found not to be of interest after somewhat more careful examination. Of all references obtained, 150 were found to contain information of direct or indirect usefulness in this project. There are two general subject areas for which references were identified and reviewed but which are not discussed in this report. These are *helmet retention* and *fit testing*. Pertinent papers, articles, and reports are listed in Table 1.

Table 1. Helmet Retention and Fit Testing References

Helmet Retention

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Reading, T. E.; Haley, J. L., Jr.; Sippo, A. C.; Licina, J.; Schopper, A. W. 1984. SPH-4 U.S. Army flight helmet performance, 1972-1983.

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Fit Testing

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Whitestone, J. J. 1993. Design and evaluation of helmet systems using 3D data.

A1.0 ANTHROPOMETRIC SURVEYS

Three military anthropometric projects were identified from the literature search as being of potential usefulness in the present study. These are: 1) the Tri-Service database, 2) the CARD database, and 3) the ANSUR database. The database selected for use in the study was the ANSUR database. The factors that resulted in this choice are discussed in Section A1.3.

A fourth database, the CAMI database of adult civilian head and face anthropometry was given brief consideration. The description of this database may be found in *Head and Face Anthropometry of Adult U.S. Citizens* (J. W. Young; 1993). This database might have been useful except for its small size (195 females and 172 males) and the fact that no facial landmark coordinate data are available.

A1.1 The Tri-Service Database

The Tri-Service database is the culmination of a project begun at the U.S. Army Aeromedical Research Laboratory (USAARL) in 1980. Its development was coordinated by the Tri-Service Working Group on Biomechanics of the Tri-Service Committee of the Tri-Service Aeromedical Research Panel. While the

Army, Navy, and Air Force all participated in the development of the database, the data are mostly from a 1967 survey of U.S. Air Force rated male aircrew. Data represent 3rd, 50th, and 95th percentile aircrew as defined from stature and weight multiple regression equations. The 1967 data were projected, by a technique of Churchill and McConville (1976), to reflect assumed increases in body size from 1967 to the 1980-1990 time period. Some dimensions not measured in the 1967 survey were derived from other data in that survey or estimated from other surveys. There are no coordinate data for anatomical landmarks in the Tri-Service database; i.e., only "standard" anthropometric dimensional measurements are available.

Head and face dimensions in the Tri-Service database, like all other dimensions-- such as sitting height, hip width, etc.-- are based on multiple regressions on stature and weight. That is, head and face dimensions, like all other dimensions, are assumed to be proportional to stature and weight, being of the form

$$\text{(head/face dimension)} = C_1 * \text{(stature)} + C_2 * \text{(weight)} + C_3$$

where C_1, C_2, and C_3 are regression constants. This is not a good assumption, however, as head sizes and facial dimensions of adults tend to be independent from body size.

The unavailability of coordinate data for anatomical landmarks and the implicit assumption of a proportional dependence of head and face dimensions on stature and weight are factors which make the Tri-Service database of questionable usefulness for the particular application of the present study, i.e., development of small, midsized, and large headforms. An additional factor is that the database includes no data for female subjects, which need to be utilized in the present study.

The Tri-Service database is described and documented in a Tri-Service report: *Anthropometry and Mass Distribution for Human Analogues--Volume I: Military Aviators* (1988). Other pertinent reports are *The AMRL Anthropometric Data Bank Library: Volumes I-V* (E. Churchill, P. Kikta, and T. Churchill; 1977) and *Sampling and Data Gathering Strategies for Future USAF Anthropometry* (Churchill and McConville; 1976).

A1.2 The CARD Database

The Anthropometric Database at the U.S. Air Force Computerized Anthropometric Research and Design (CARD) Laboratory is operated by AL/CFHD at Wright-Patterson AFB, Ohio. Access to the database is through menu-driven applications software. The database presently contains data for anthropometric variables collected in nine different surveys. Five of the surveys are of Air Force personnel, and there are three for Army and one for Navy personnel. There are databases for both males and females. The earliest survey in the CARD Anthropometric Database is 1965 and the latest is 1977.

Data may be selected by body region, of which head and neck is one, as well as by type, e.g., arcs, breadths, circumferences, etc. The numeric data available are summary statistics and frequency data for each measurement. As with the Tri-Service database, there are no coordinate data for anatomical landmarks in the CARD Anthropometric Database; i.e., only "standard" anthropometric dimensional measurements are available, and it would therefore be difficult to establish facial surface contour details using this database. Further, as with the Tri-Service database, data for individual subjects seem not to be available, which makes it impossible to do regression studies for independent variables not selected by the CARD Laboratory for determination of summary statistics (even though regression coefficients for some independent variables may be available). These two factors, together with the fact that the data are 20-30 years old and thus not entirely representative of the 1990s population, make it doubtful that this database could be used effectively to meet the particular goals of the present study.

The CARD Anthropometric Database is described and documented in a CARD report: *User's Guide to the Anthropometric Database at the Computerized Anthropometric Research and Design (CARD) Laboratory: Second Edition* (J. Robinson, K. Robinette, and G. Zehner; 1992). Another pertinent report is *User's Guide to Accessing the Anthropometric Data Base at the Center for Anthropometric Reseach Data* (same authors; 1988).

[The U.S. Air Force also has a database called the AAMRL Biodynamics Data Bank, which contains both dynamic test response data and anthropometry data. This database is described in *The AAMRL Biodynamics Data Bank* (J. Abrams, I. Kaleps, J. Brinkley; 1988). This database was not given consideration because its anthropometry data content is too limited.]

A1.3 The ANSUR Database

The U.S. Army Anthropometric Survey (ANSUR) was conducted in 1987-1988. Approximately 26,000 subjects at 11 Army bases were screened for the survey. A sampling strategy described in the final report reduced the number of subjects to be fully measured to about 9,000. From the measured survey sample a final survey database of 3,982 subjects was determined in such a manner as to reflect the proportions of men and women in various racial/ethnic and age groups found in the June, 1988 Army. Measurement data for 1,774 men and 2,208 women comprise the working database.

At each Army base the subjects were measured for 132 dimensions at a series of measuring stations. Portable personal computers were independently operated at each of the measuring stations, from the in-processing station through the out-processing station, for recording and verifying data with a custom-designed computer data entry and editing system. Each subject carried a floppy diskette with his/her data from station to station.

In addition to the 132 standard dimensions measured for each subject, head and face data were determined by use of an automated headboard device (AHD). Twenty-six head and face landmarks were selected for automated measurement of coordinates. The landmarks selected were chosen on the basis of their usefulness in the design of helmets, respirators, goggles, and other personal protective equipment.

In the final report ("Methods and Summary Statistics") data for each measurement are given in terms of percentiles and frequency tables for males and females separately. Values for percentiles 1, 2, 3, 5, 10, 15, ..., 90, 95, 97, 98, 99 are tabulated, and frequencies are given for steps of from 0.1 to 1.5 cm, depending on the particular dimension. The coordinate data for head and face landmarks are not included in these tables, but, instead, tables are included for 48 dimensions derived from the coordinate data--e.g., Z_{menton} minus $Z_{top\text{-}of\text{-}head}$ is given as a measure of head height.

Several factors recommend the ANSUR data as preferable to the Tri-Service data or the CARD data for use in the present study. One is the currency of the data--1988 in contrast to 1967 data projected to 1980-1990 in the case of Tri-Service and 1965-1977, unprojected data in the case of CARD. A second is that the ANSUR database includes data for females, as well as data for males (separately). (The CARD database also includes data for females.) Third, "raw" data for head and face dimensions are present in the database; i.e., head and face data have not been reduced to values for small, midsized, and large *overall size* by regressions on *stature and weight* as in the case of the Tri-Services database. It is absolutely necessary to be able to establish shape and dimensions for small, midsized, and large *heads and faces* on the basis of independent variables specific to the head and face. Fourth, in order to do regressions or any other type of modeling, data for all subjects--not just reduced data, frequency data, and summary data--are needed, and those data are available for the ANSUR study. Fifth, the ANSUR data may be more accurate than the data in the other two databases-- particularly the head and face data, which were determined from use of the Automated Headboard Device--since a computer data entry and editing system was used. Finally, coordinate data for head and facial landmarks, while not in the printed report, are available (for all subjects), and such data are considered vital for establishing the shape and dimensional specifications for headforms in the present study.

The ANSUR database is described and documented in a series of reports. The primary ones relevant to the present study are: *1988 Anthropometric Survey of U.S. Army Personnel - Methods and Summary Statistics* (Gordon, C. C., et al.; 1989), and *The Development and Validation of an Automated Headboard Device for Measurement of Three-dimensional Coordinates of the Head and Face* (J. F. Annis and C. C. Gordon; 1988).

[Note: From the approximately 9,000 subjects who were fully measured, Natick also developed a subset database of 487 male pilots and 334 females who met the 1988 anthropometric criteria for entry into pilot training. That database is described in *1988 Anthropometric Survey of U.S. Army Personnel: Pilot Summary Statistics* (S. M. Donelson and C. C. Gordon; 1991). This database was not considered for use in this study because it is only one-fifth as large as the working database described, which we considered too small for the type of anthropometric modeling to be conducted. It was believed, additionally, that there would be no important differences in head and face dimensions between the pilot and general populations of the U.S. Army. That this is correct is suggested by the pilot-vs.-general population comparisons of average values for variables such as arm length, chest depth, and sitting height on pages 2 and 3 of that reference. (No head or face measures are included in the comparisons.) Dr. Claire C. Gordon of Natick, a coauthor, has also stated in a personal communication that she agrees that pilot head and face data would not be significantly different from data for the general U.S. Army population.]

A2.0 DATA ANALYSIS

After the decision was made that the ANSUR database is the one most suitable for meeting the objectives of the project, contacts were made with Dr. Claire C. Gordon of U.S. Army Natick Research, Development and Engineering Center, the principal investigator of the 1988 Anthropometric Survey of U.S. Army personnel. Dr. Gordon agreed to make all requested data available for use in the headform study. Dr. Brian Corner of GEO-CENTERS, Inc., a task order contractor to Natick, prepared the data files and sent them on floppy diskette. The first data sets received were incomplete, so additional diskettes were obtained. The data files were put into a different format, and the head and face landmark coordinate data were merged with the anthropometric variables data.

Table 2 shows the format of the ANSUR data files. There is one file for the 1,774 male subjects and one file for the 2,208 female subjects. A subject-by-subject layout is used for these files. The files include data for several biographical variables (sex, age, race, and MOS), weight, stature, neck circumference, 16 head and face traditional anthropometric variables, and coordinate positions of 26 head and face landmarks.

Table 2. Layout of ANSUR Data Files

```
MWDBXYZ.VAR (1774 subjects)**|
MEN1.VAR (5692 subjects)     |---> MWDBXYZ.MER (1774 subjects)**

WWDBXYZ.VAR (2208 subjects)  |
WOM1.VAR (3599 subjects)     |---> WWDBXYZ.MER (2208 subjects)
-----------------------------------------------------------------
```

** NOTE: The MWDBXYZ.VAR originally received included complete data for only 1665 (male) subjects. The missing data for 109 subjects was requested and received on August 1, 1994. The files MWDBXYZ.VAR, MWDBXYZ.MER, and VAR.MER (this file) have been modified accordingly.

The files are sequential with ASCII format. Length variable values are in mm and are space delimited. Weight is kilograms multiplied by 10. Head/face X, Y, and Z values are in unitsof 0.1 mm (i.e., values are mm multiplied by 10).

line 1: SUBJNO, SEX, AGE, RACESUBJ, MOSPRIM
line 2: NECKCIRC (80), WEIGHT (124), STATURE (99)
line 3: SUBJNO ... ... (head/face dimensions: 7 values) ... ...

Field
1 SUBJNO
2 HEADLGTH (62)
3 HEADBRTH (60)
4 HEADCIRC (61)
5 BITCHARC (15)
6 BITCOARC (16)
7 BITCRARC (17)
8 BITFRARC (18)

line 4: … … (head/face dimensions: 9 values) … …

1 BITSMARC (19)
2 BITSNARC (20)
3 BIZBDTH (21)
4 EARBDTH (43)
5 EARLGTH (44)
6 EARLTRAG (45)
7 EARPROT (46)
8 INPUPBTH (68)
9 MENSELL (77)

lines 5-30 are the head/face landmark X, Y, and Z coordinates:

The (X,Y,Z) coordinate data have units of 0.1 mm. The origin is in the upper left corner if you are facing an individual. The AHD machine was zeroed out above and slightly behind the right shoulder at the top of the head. X is positive forward, Y is positive to the subject's left, and Z is positive downward.

line 5: CRINON
line 6: GLABELLA
line 7: SELLION
line 8: PRONASALE
line 9: SUBNASALE
line 10: STOMION
line 11: PROMENTON
line 12: MENTON
line 13: R GONION
line 14: L GONION
line 15: R CHEILION
line 16: L CHEILION
line 17: R ALARE
line 18: L ALARE
line 19: R TRAGION
line 20: L TRAGION
line 21: R INFRAORBITALE
line 22: L INFRAORBITALE
line 23: R ECTOORBITALE
line 24: L ECTOORBITALE
line 25: R ZYGION
line 26: L ZYGION
line 27: R ZYGOFRONTALE

line 28: L ZYGOFRONTALE
line 29: R FRONTOTEMPORALE
line 30: L FRONTOTEMPORALE

BIOGRAPHICAL DATA (line 1)
SEX -- 1=male, 2=female
AGE -- in years
RACESUBJ -- a composite of all the ethnic/race components in a subject's family. Numbers reflect subject's identify and family background. The numbers are 1-white, 2-black, 3-Hispanic, 4-Asian, 5-Native American, 6-Caribbean islander, 7-East Indian (Continental India and surrounding areas), 8-Arab. Order reflects percentage in the Army population. Mixed race individuals are indicated by a RACESUBJ > 8. For example, a person with Hispanic and black parents who considers him/herself black would be coded 23. Thus, someone with a RACESUBJ of 435 would be Asian (primarily) with Hispanic and Native American admixture.
MOSPRIM (Military Occupation Specialty) -- See Table 25 in the ANSUR final report (pp. 50-51) for definitions.

APPENDIX B

MULTIVARIATE LIMIT ANALYSIS TABLES

LIST OF TABLES

Table 1. Dimensions of a Small Headform (Method 1)
Full Body Weight = 60.50 Kg Stature = 1623.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			185.900
Head Breadth*			142.450
Head Circumference*			538.100
Menton-Sellion*			112.150
neck circumference	314.193	18.618	310.000
bitragion chin arc	299.873	12.279	299.000
bitragion coronal arc	331.162	9.391	331.000
bitragion crinion arc	304.183	8.154	304.000
bitragion frontal arc	284.878	7.051	284.000
bitragion subman. arc	274.599	12.964	273.000
bitragion subnas. arc	272.883	9.553	272.000
bizygomatic breadth	129.929	3.978	130.000
ear breadth	34.665	2.509	34.000
ear length	59.401	4.113	59.000
ear length above tragion	57.741	7.206	59.000
ear protrusion	21.838	2.990	22.000
interpupillary breadth	61.381	3.002	61.000
H1 alare-back of head	189.227	4.565	189.100
H2 alare-top of head	145.167	6.263	145.500
H3 bigonial breadth	107.732	6.943	107.180
H4 biinfraorbitale breadth	66.515	4.425	66.010
H5 biocular breadth, max	117.819	4.695	117.400
H6 bitragion breadth	135.211	4.399	135.280
H7 bizygomatic breadth	134.051	4.531	133.830
H8 cheilion-back of head	177.533	6.780	176.600
H9 cheilion-top of head	175.366	5.932	175.050
H10 chin-back of head	185.350	7.683	184.600
H11 chin-top of head	200.824	6.583	200.400
H12 crinion-back of head	177.002	6.191	178.400
H13 crinion-top of head	40.519	8.919	40.600
H14 ectoorbitale-back of head	151.585	3.857	151.550
H15 ectoorbitale-top of head	110.328	4.924	110.150
H16 frontotemporale-back of head	163.908	3.220	164.350
H17 frontotemporale-top of head	83.257	6.125	83.650
H18 glabella-back of head	188.915	2.339	188.800
H19 glabella-top of head	87.258	6.363	87.200
H20 gonion-back of head	105.408	5.777	105.200
H21 gonion-top of head	179.943	5.955	179.450
H22 infraorbitale-back of head	173.837	3.928	174.000
H23 infraorbitale-top of head	122.690	5.011	122.750
H24 lip length	53.844	3.956	53.780
H25 maximum frontal breadth	109.710	4.814	109.930
H26 menton_back of head	171.746	7.843	171.600

* Median values for these measurements are actually multivariate 5th percentile values.

Table 1. Dimensions of a Small Headform (Method 1)
Full Body Weight = 60.50 Kg Stature = 1623.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	175.184	7.719	175.790
H28 menton-sellion length	112.535	2.827	112.580
H29 menton-subnasale length	67.823	3.557	67.850
H30 menton-top of head	215.178	5.919	215.100
H31 min. frontal breadth	102.278	3.968	102.020
H32 nose breadth	33.468	4.286	32.740
H33 nose protrusion	18.121	2.215	18.060
H34 pronasale-back of head	207.877	4.234	208.000
H35 pronasale-top of head	140.259	7.231	140.600
H36 sellion-back of head	187.050	2.809	187.000
H37 sellion top of head	103.985	5.789	104.300
H38 stomion-back of head	190.606	7.321	190.000
H39 stomion-top of head	173.278	6.151	173.000
H40 subnasale-back of head	193.817	4.998	194.000
H41 subnasale-sellion length	48.058	3.130	48.110
H42 subnasale-top of head	151.329	6.568	151.700
H43 tragion-back of head	95.973	3.632	96.150
H44 tragion-top of head	121.975	4.791	122.150
H45 zygion-back of head	126.171	5.392	126.100
H46 zygion-top of head	124.696	4.518	124.650
H47 zygofrontale-back of head	160.262	3.809	160.250
H48 zygofrontale-top of head	97.311	5.578	97.350

Table 2. Dimensions of a Medium Headform (Method 1)
Full Body Weight = 75.30 Kg Stature = 1731.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			195.200
Head Breadth*			151.850
Head Circumference*			563.500
Menton-Sellion*			123.040
neck circumference	365.959	26.589	371.000
bitragion chin arc	321.386	12.009	322.000
bitragion coronal arc	351.832	9.894	352.000
bitragion crinion arc	323.061	8.802	323.000
bitragion frontal arc	301.178	7.800	300.000
bitragion subman. arc	298.792	14.512	299.000
bitragion subnas. arc	288.528	10.354	289.000
bizygomatic breadth	138.949	5.176	139.000
ear breadth	37.203	2.828	37.000
ear length	63.751	4.268	64.000
ear length above tragion	38.761	12.797	33.000
ear protrusion	23.497	3.168	23.000
interpupillary breadth	64.030	3.487	64.000
H1 alare-back of head	197.864	5.165	197.900
H2 alare-top of head	154.297	6.485	154.750
H3 bigonial breadth	117.082	7.890	117.220
H4 biinfraorbitale breadth	68.271	4.920	68.140
H5 biocular breadth, max	121.461	4.949	121.060
H6 bitragion breadth	143.415	5.388	143.150
H7 bizygomatic breadth	141.917	5.602	141.680
H8 cheilion-back of head	184.165	7.149	183.500
H9 cheilion-top of head	186.579	6.230	186.700
H10 chin-back of head	192.421	7.787	193.000
H11 chin-top of head	215.431	6.685	215.100
H12 crinion-back of head	182.681	7.618	183.800
H13 crinion-top of head	41.906	9.573	42.300
H14 ectoorbitale-back of head	158.836	3.459	158.550
H15 ectoorbitale-top of head	116.992	5.063	117.000
H16 frontotemporale-back of head	172.531	3.322	172.400
H17 frontotemporale-top of head	89.242	6.107	89.200
H18 glabella-back of head	197.688	2.831	197.700
H19 glabella-top of head	94.285	6.967	93.700
H20 gonion-back of head	115.087	6.283	114.900
H21 gonion-top of head	194.980	7.900	194.600
H22 infraorbitale-back of head	180.128	4.075	180.100
H23 infraorbitale-top of head	129.567	5.168	129.900
H24 lip length	55.351	4.247	55.320
H25 maximum frontal breadth	112.765	5.050	112.540
H26 menton_back of head	180.038	8.071	179.300

* Median values for these measurements are actually multivariate 50th percentile values.

Table 2. Dimensions of a Medium Headform (Method 1)
Full Body Weight = 75.30 Kg Stature = 1731.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	189.065	8.507	188.420
H28 menton-sellion length	121.360	3.330	121.230
H29 menton-subnasale length	73.357	3.990	73.190
H30 menton-top of head	230.470	6.038	230.100
H31 min. frontal breadth	104.535	4.885	104.670
H32 nose breadth	35.824	4.225	35.130
H33 nose protrusion	19.258	2.306	19.220
H34 pronasale-back of head	217.340	4.944	217.600
H35 pronasale-top of head	150.126	7.349	150.600
H36 sellion-back of head	195.348	3.260	195.300
H37 sellion top of head	110.377	5.912	110.500
H38 stomion-back of head	197.747	7.709	197.500
H39 stomion-top of head	184.835	6.446	185.000
H40 subnasale-back of head	201.503	5.703	201.900
H41 subnasale-sellion length	50.877	3.207	50.520
H42 subnasale-top of head	160.650	6.735	161.300
H43 tragion-back of head	98.506	4.260	98.600
H44 tragion-top of head	130.000	4.927	130.050
H45 zygion-back of head	131.697	5.122	131.550
H46 zygion-top of head	130.978	4.810	130.800
H47 zygofrontale-back of head	169.278	3.434	169.300
H48 zygofrontale-top of head	104.764	5.763	104.950

Table 3. Dimensions of a Large Headform (Method 1)
Full Body Weight = 88.10 Kg   Stature = 1790.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			210.700
Head Breadth*			161.250
Head Circumference*			595.250
Menton-Sellion*			133.170
neck circumference	395.218	18.973	394.000
bitragion chin arc	337.325	12.367	338.000
bitragion coronal arc	365.396	11.520	365.000
bitragion crinion arc	337.929	10.815	338.000
bitragion frontal arc	316.147	9.031	316.000
bitragion subman. arc	314.985	14.060	315.000
bitragion subnas. arc	301.563	9.477	301.000
bizygomatic breadth	144.726	4.719	145.000
ear breadth	38.670	2.828	39.000
ear length	65.797	4.546	66.000
ear length above tragion	32.853	5.362	32.000
ear protrusion	24.497	3.497	24.000
interpupillary breadth	67.112	3.547	67.000
H1 alare-back of head	208.186	6.366	208.300
H2 alare-top of head	160.323	7.970	159.950
H3 bigonial breadth	123.630	7.153	123.820
H4 biinfraorbitale breadth	71.118	4.893	70.880
H5 biocular breadth, max	126.094	5.044	125.220
H6 bitragion breadth	148.867	5.225	148.630
H7 bizygomatic breadth	148.099	5.082	147.900
H8 cheilion-back of head	193.095	8.053	193.000
H9 cheilion-top of head	194.506	7.543	193.850
H10 chin-back of head	202.096	9.380	201.500
H11 chin-top of head	224.982	8.715	224.800
H12 crinion-back of head	192.443	8.621	193.100
H13 crinion-top of head	42.909	10.925	42.900
H14 ectoorbitale-back of head	167.034	4.960	167.200
H15 ectoorbitale-top of head	121.755	6.561	122.050
H16 frontotemporale-back of head	181.895	4.686	181.950
H17 frontotemporale-top of head	92.619	8.007	92.100
H18 glabella-back of head	209.121	4.559	209.100
H19 glabella-top of head	99.060	8.645	99.100
H20 gonion-back of head	122.746	7.545	122.450
H21 gonion-top of head	204.398	7.175	203.950
H22 infraorbitale-back of head	189.086	5.081	189.050
H23 infraorbitale-top of head	134.630	6.319	134.150
H24 lip length	57.856	4.014	57.690
H25 maximum frontal breadth	117.698	4.747	117.530
H26 menton_back of head	189.275	9.982	189.000

* Median values for these measurements are actually multivariate 95th percentile values.

Table 3. Dimensions of a Large Headform (Method 1)
Full Body Weight = 88.10 Kg   Stature = 1790.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	198.722	9.738	197.540
H28 menton-sellion length	126.742	5.355	125.960
H29 menton-subnasale length	77.675	5.013	77.510
H30 menton-top of head	241.059	8.394	241.100
H31 min. frontal breadth	109.770	4.657	109.910
H32 nose breadth	38.341	5.010	37.150
H33 nose protrusion	19.299	2.528	19.340
H34 pronasale-back of head	227.948	6.483	227.500
H35 pronasale-top of head	156.857	9.340	156.800
H36 sellion-back of head	205.812	4.989	205.500
H37 sellion top of head	115.734	7.978	114.700
H38 stomion-back of head	208.126	8.482	207.700
H39 stomion-top of head	192.976	8.027	192.900
H40 subnasale-back of head	211.901	6.873	211.500
H41 subnasale-sellion length	51.964	3.657	51.870
H42 subnasale-top of head	167.085	8.157	166.600
H43 tragion-back of head	104.162	5.174	104.300
H44 tragion-top of head	135.090	6.046	134.850
H45 zygion-back of head	138.626	5.182	138.350
H46 zygion-top of head	135.564	6.105	135.600
H47 zygofrontale-back of head	178.642	4.853	178.900
H48 zygofrontale-top of head	109.526	7.002	109.400

Table 4. Dimensions of a Small Headform (Method 2)
Full Body Weight = 59.90 Kg   Stature = 1615.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			185.900
Head Breadth*			142.450
Head Circumference*			535.490
H30 Menton-Top of Head*			214.420
neck circumference	313.223	17.436	311.000
bitragion chin arc	298.249	11.658	298.000
bitragion coronal arc	330.360	8.192	330.000
bitragion crinion arc	303.005	7.146	303.000
bitragion frontal arc	284.051	6.830	283.000
bitragion subman. arc	272.452	13.113	272.000
bitragion subnas. arc	272.041	9.249	272.000
bizygomatic breadth	129.208	4.245	129.000
ear breadth	34.827	2.439	35.000
ear length	59.173	3.734	59.000
ear length above tragion	57.893	6.351	59.000
ear protrusion	21.904	3.154	22.000
interpupillary breadth	61.274	3.162	61.000
H1 alare-back of head	188.928	4.554	188.850
H2 alare-top of head	144.821	4.024	144.900
H3 bigonial breadth	106.955	6.657	106.510
H4 biinfraorbitale breadth	66.375	4.547	65.720
H5 biocular breadth, max	117.652	4.782	117.010
H6 bitragion breadth	134.710	3.967	134.520
H7 bizygomatic breadth	133.553	4.481	133.410
H8 cheilion-back of head	177.285	6.894	176.950
H9 cheilion-top of head	175.005	3.652	175.450
H10 chin-back of head	184.872	7.145	184.400
H11 chin-top of head	200.123	4.170	199.800
H12 crinion-back of head	177.185	6.094	178.100
H13 crinion-top of head	41.453	7.939	41.800
H14 ectoorbitale-back of head	151.191	3.857	151.400
H15 ectoorbitale-top of head	110.011	3.856	110.000
H16 frontotemporale-back of head	163.676	3.492	163.800
H17 frontotemporale-top of head	82.839	5.375	83.400
H18 glabella-back of head	188.692	2.637	188.800
H19 glabella-top of head	87.281	5.444	87.600
H20 gonion-back of head	104.855	6.008	104.700
H21 gonion-top of head	179.617	4.769	179.600
H22 infraorbitale-back of head	173.505	3.864	173.350
H23 infraorbitale-top of head	122.471	3.588	122.450
H24 lip length	53.665	4.002	53.410
H25 maximum frontal breadth	109.647	4.638	109.480
H26 menton_back of head	170.969	7.507	170.800

* Median values for these measurements are actually multivariate 5th percentile values.

Table 4. Dimensions of a Small Headform (Method 2)
Full Body Weight = 59.90 Kg Stature = 1615.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	173.748	7.842	173.310
H28 menton-sellion length	112.346	4.405	111.600
H29 menton-subnasale length	67.881	3.935	67.050
H31 min. frontal breadth	101.730	4.297	101.490
H32 nose breadth	33.746	4.450	32.720
H33 nose protrusion	18.071	2.120	17.820
H34 pronasale-back of head	207.534	4.351	207.800
H35 pronasale-top of head	140.038	5.094	139.800
H36 sellion-back of head	186.775	3.112	186.800
H37 sellion top of head	103.759	4.793	104.100
H38 stomion-back of head	190.334	6.980	189.900
H39 stomion-top of head	172.929	3.939	173.200
H40 subnasale-back of head	193.372	4.757	193.700
H41 subnasale-sellion length	47.816	3.292	47.600
H42 subnasale-top of head	150.922	4.500	151.200
H43 tragion-back of head	95.711	3.876	95.700
H44 tragion-top of head	121.929	3.668	122.150
H45 zygion-back of head	126.093	5.566	125.950
H46 zygion-top of head	124.351	3.611	124.350
H47 zygofrontale-back of head	159.797	3.850	159.650
H48 zygofrontale-top of head	97.231	4.643	97.350

Table 5. Dimensions of a Medium Headform (Method 2)
Full Body Weight = 74.70 Kg Stature = 1726.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			195.200
Head Breadth*			152.260
Head Circumference*			563.500
H30 Menton-Top of Head*			230.200
neck circumference	365.066	27.949	371.000
bitragion chin arc	319.584	11.749	320.000
bitragion coronal arc	352.635	8.908	353.000
bitragion crinion arc	323.218	8.881	324.000
bitragion frontal arc	301.061	8.023	300.000
bitragion subman. arc	297.005	14.124	297.000
bitragion subnas. arc	288.244	9.822	288.000
bizygomatic breadth	138.579	5.003	138.000
ear breadth	37.015	2.747	37.000
ear length	63.772	4.197	64.000
ear length above tragion	38.893	12.934	33.000
ear protrusion	23.741	3.270	24.000
interpupillary breadth	64.152	3.325	64.000
H1 alare-back of head	197.274	4.971	197.300
H2 alare-top of head	154.837	4.550	154.950
H3 bigonial breadth	116.702	7.999	116.240
H4 biinfraorbitale breadth	68.034	4.899	67.940
H5 biocular breadth, max	121.208	4.806	120.790
H6 bitragion breadth	142.892	5.287	142.800
H7 bizygomatic breadth	141.580	5.571	141.510
H8 cheilion-back of head	183.216	6.549	183.100
H9 cheilion-top of head	186.833	3.835	186.850
H10 chin-back of head	191.612	7.083	191.800
H11 chin-top of head	215.530	4.070	215.400
H12 crinion-back of head	183.606	7.381	184.300
H13 crinion-top of head	43.126	8.951	43.100
H14 ectoorbitale-back of head	158.570	3.510	158.450
H15 ectoorbitale-top of head	117.635	4.028	117.800
H16 frontotemporale-back of head	172.643	3.164	172.450
H17 frontotemporale-top of head	90.358	5.352	90.600
H18 glabella-back of head	197.765	2.764	197.800
H19 glabella-top of head	95.463	5.746	95.100
H20 gonion-back of head	114.677	6.726	114.800
H21 gonion-top of head	194.669	6.877	194.350
H22 infraorbitale-back of head	179.789	3.937	179.600
H23 infraorbitale-top of head	130.308	3.895	130.400
H24 lip length	55.495	4.191	55.640
H25 maximum frontal breadth	112.520	4.728	111.870
H26 menton_back of head	179.444	7.565	178.800

* Median values for these measurements are actually multivariate 50th percentile values.

Table 5. Dimensions of a Medium Headform (Method 2)
Full Body Weight = 74.70 Kg Stature = 1726.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	187.225	8.849	186.090
H28 menton-sellion length	119.738	4.598	119.660
H29 menton-subnasale length	72.300	4.161	72.160
H31 min. frontal breadth	104.396	4.618	104.600
H32 nose breadth	35.787	4.400	34.910
H33 nose protrusion	18.870	2.316	18.670
H34 pronasale-back of head	216.677	5.070	216.500
H35 pronasale-top of head	151.010	5.683	151.000
H36 sellion-back of head	195.176	3.136	194.800
H37 sellion top of head	111.482	4.657	111.400
H38 stomion-back of head	196.881	7.085	196.100
H39 stomion-top of head	185.274	4.101	185.100
H40 subnasale-back of head	201.099	5.488	201.200
H41 subnasale-sellion length	50.310	3.688	50.150
H42 subnasale-top of head	161.230	4.818	161.500
H43 tragion-back of head	98.195	4.253	98.200
H44 tragion-top of head	130.347	3.955	130.400
H45 zygion-back of head	131.381	4.921	131.300
H46 zygion-top of head	131.355	4.325	131.250
H47 zygofrontale-back of head	169.281	3.402	169.100
H48 zygofrontale-top of head	105.588	4.730	105.750

Table 6. Dimensions of a Large Headform (Method 2)
Full Body Weight = 88.10 Kg Stature = 1792.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			210.700
Head Breadth*			161.250
Head Circumference*			595.250
H30 Menton-Top of Head*			246.810
neck circumference	395.503	20.139	395.000
bitragion chin arc	337.076	12.356	336.000
bitragion coronal arc	367.812	10.488	368.000
bitragion crinion arc	339.401	10.246	339.000
bitragion frontal arc	316.782	8.878	316.000
bitragion subman. arc	315.030	14.729	315.000
bitragion subnas. arc	301.711	9.755	301.000
bizygomatic breadth	144.751	5.159	144.000
ear breadth	38.624	2.852	39.000
ear length	65.746	4.653	66.000
ear length above tragion	32.609	4.984	32.000
ear protrusion	24.482	3.434	24.000
interpupillary breadth	67.168	3.601	67.000
H1 alare-back of head	207.381	6.752	207.150
H2 alare-top of head	162.237	6.424	161.500
H3 bigonial breadth	124.055	7.362	124.130
H4 biinfraorbitale breadth	70.855	4.973	70.900
H5 biocular breadth, max	125.791	5.359	124.870
H6 bitragion breadth	148.953	5.657	148.510
H7 bizygomatic breadth	148.271	5.533	147.900
H8 cheilion-back of head	192.060	8.376	191.250
H9 cheilion-top of head	196.251	6.106	195.550
H10 chin-back of head	201.218	9.328	200.700
H11 chin-top of head	226.744	7.122	226.100
H12 crinion-back of head	193.659	7.671	194.100
H13 crinion-top of head	44.958	10.324	44.700
H14 ectoorbitale-back of head	166.936	5.172	166.900
H15 ectoorbitale-top of head	123.530	5.628	123.650
H16 frontotemporale-back of head	181.961	4.870	182.050
H17 frontotemporale-top of head	94.747	7.450	95.050
H18 glabella-back of head	209.061	4.827	209.000
H19 glabella-top of head	101.582	7.264	101.300
H20 gonion-back of head	122.186	7.472	121.450
H21 gonion-top of head	205.685	6.404	205.750
H22 infraorbitale-back of head	188.607	5.429	188.050
H23 infraorbitale-top of head	136.342	5.398	136.050
H24 lip length	58.093	3.921	57.990
H25 maximum frontal breadth	117.574	4.903	117.480
H26 menton_back of head	188.447	9.814	187.100

* Median values for these measurements are actually multivariate 95th percentile values.

Table 6. Dimensions of a Large Headform (Method 2)
Full Body Weight = 88.10 Kg Stature = 1792.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H27 menton-crinion length	198.160	9.868	197.160
H28 menton-sellion length	126.031	5.608	125.550
H29 menton-subnasale length	77.323	5.004	77.170
H31 min. frontal breadth	109.643	4.907	109.570
H32 nose breadth	38.469	4.832	37.350
H33 nose protrusion	19.189	2.471	19.110
H34 pronasale-back of head	227.137	6.680	226.400
H35 pronasale-top of head	158.963	7.706	158.700
H36 sellion-back of head	205.496	5.248	205.200
H37 sellion top of head	118.035	6.743	117.500
H38 stomion-back of head	207.213	8.683	206.300
H39 stomion-top of head	194.758	6.415	193.600
H40 subnasale-back of head	211.077	7.177	210.400
H41 subnasale-sellion length	51.515	3.806	51.240
H42 subnasale-top of head	169.012	6.611	168.100
H43 tragion-back of head	103.613	5.210	103.500
H44 tragion-top of head	136.522	5.112	136.300
H45 zygion-back of head	138.053	5.537	137.800
H46 zygion-top of head	137.088	5.402	137.100
H47 zygofrontale-back of head	178.515	5.072	178.600
H48 zygofrontale-top of head	111.472	6.070	111.100

Table 7. Dimensions of a Small Headform (Method 3)
Full Body Weight = 57.60 Kg Stature = 1612.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			185.060
Head Breadth*			142.450
Head Circumference*			531.750
neck circumference	311.325	17.914	309.000
bitragion chin arc	298.345	11.872	298.000
bitragion coronal arc	328.716	9.658	329.000
bitragion crinion arc	301.178	8.431	301.000
bitragion frontal arc	282.350	7.583	283.000
bitragion subman. arc	273.239	13.041	272.000
bitragion subnas. arc	271.716	9.576	270.000
bizygomatic breadth	129.005	4.477	128.000
ear breadth	34.888	2.358	35.000
ear length	59.802	3.327	60.000
ear length above tragion	58.112	7.295	60.000
ear protrusion	22.091	3.185	22.000
interpupillary breadth	61.168	3.237	61.000
H1 alare-back of head	187.689	4.781	187.900
H2 alare-top of head	144.266	6.603	144.300
H3 bigonial breadth	106.778	6.663	106.230
H4 biinfraorbitale breadth	65.717	4.775	65.240
H5 biocular breadth, max	117.119	4.700	116.540
H6 bitragion breadth	134.426	4.906	134.230
H7 bizygomatic breadth	133.120	4.885	132.620
H8 cheilion-back of head	175.921	6.915	175.050
H9 cheilion-top of head	174.319	6.620	174.700
H10 chin-back of head	184.153	7.611	183.600
H11 chin-top of head	199.406	7.632	199.700
H12 crinion-back of head	175.476	6.518	175.700
H13 crinion-top of head	41.063	9.103	41.200
H14 ectoorbitale-back of head	150.018	3.570	149.600
H15 ectoorbitale-top of head	109.641	5.333	109.900
H16 frontotemporale-back of head	162.464	3.327	162.100
H17 frontotemporale-top of head	82.797	6.242	83.400
H18 glabella-back of head	187.411	2.814	187.300
H19 glabella-top of head	87.238	6.587	87.200
H20 gonion-back of head	104.269	6.252	104.100
H21 gonion-top of head	179.482	5.715	179.850
H22 infraorbitale-back of head	172.241	3.951	172.000
H23 infraorbitale-top of head	122.069	5.283	122.500
H24 lip length	54.294	3.903	53.870
H25 maximum frontal breadth	108.969	4.703	108.810
H26 menton_back of head	170.480	8.113	170.100
H27 menton-crinion length	173.314	8.597	172.310

* Median values for these measurements are actually multivariate 5th percentile values.

Table 7. Dimensions of a Small Headform (Method 3)
Full Body Weight = 57.60 Kg Stature = 1612.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H28 menton-sellion length	111.629	5.801	111.380
H29 menton-subnasale length	67.288	5.100	66.810
H30 menton-top of head	213.848	7.725	214.100
H31 min. frontal breadth	101.291	4.250	101.000
H32 nose breadth	33.655	4.329	32.600
H33 nose protrusion	17.980	2.114	17.820
H34 pronasale-back of head	206.311	4.457	206.600
H35 pronasale-top of head	139.650	7.242	139.400
H36 sellion-back of head	185.613	3.143	185.500
H37 sellion top of head	103.542	6.067	103.700
H38 stomion-back of head	189.267	7.427	188.200
H39 stomion-top of head	172.188	7.000	172.300
H40 subnasale-back of head	192.243	5.200	192.700
H41 subnasale-sellion length	47.609	3.385	47.660
H42 subnasale-top of head	150.471	6.812	150.800
H43 tragion-back of head	94.878	3.922	94.900
H44 tragion-top of head	121.331	5.075	121.450
H45 zygion-back of head	125.045	5.744	124.800
H46 zygion-top of head	124.120	4.817	124.050
H47 zygofrontale-back of head	158.836	3.778	158.550
H48 zygofrontale-top of head	96.842	5.896	97.350

Table 8. Dimensions of a Medium Headform (Method 3)
Full Body Weight = 72.40 Kg Stature = 1725.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			195.200
Head Breadth*			151.850
Head Circumference*			558.140
neck circumference	360.492	30.003	368.000
bitragion chin arc	317.645	12.802	318.000
bitragion coronal arc	347.411	10.865	348.000
bitragion crinion arc	319.340	9.114	320.000
bitragion frontal arc	297.959	7.774	298.000
bitragion subman. arc	294.624	15.300	294.000
bitragion subnas. arc	286.640	10.516	288.000
bizygomatic breadth	137.695	4.363	138.000
ear breadth	36.980	2.665	37.000
ear length	63.142	4.478	63.000
ear length above tragion	39.426	13.085	33.000
ear protrusion	23.599	3.263	23.000
interpupillary breadth	63.635	3.724	63.000
H1 alare-back of head	196.919	5.145	196.600
H2 alare-top of head	152.798	7.195	153.150
H3 bigonial breadth	115.963	8.781	115.270
H4 biinfraorbitale breadth	67.565	4.904	66.890
H5 biocular breadth, max	120.619	4.907	120.270
H6 bitragion breadth	142.428	5.149	142.010
H7 bizygomatic breadth	140.810	4.972	140.600
H8 cheilion-back of head	183.371	7.246	182.900
H9 cheilion-top of head	184.770	6.856	184.650
H10 chin-back of head	191.388	8.187	191.000
H11 chin-top of head	212.884	8.176	212.800
H12 crinion-back of head	181.168	7.648	181.800
H13 crinion-top of head	41.119	10.178	39.900
H14 ectoorbitale-back of head	158.103	3.188	158.150
H15 ectoorbitale-top of head	116.082	5.688	115.700
H16 frontotemporale-back of head	171.769	2.961	171.600
H17 frontotemporale-top of head	88.405	7.321	88.100
H18 glabella-back of head	196.976	2.321	196.800
H19 glabella-top of head	93.467	7.414	93.100
H20 gonion-back of head	114.626	6.461	114.150
H21 gonion-top of head	192.510	8.102	192.550
H22 infraorbitale-back of head	179.272	3.998	179.100
H23 infraorbitale-top of head	128.614	5.755	128.750
H24 lip length	54.928	4.366	54.630
H25 maximum frontal breadth	112.148	5.262	111.210
H26 menton_back of head	178.981	8.230	178.700
H27 menton-crinion length	186.923	9.900	187.020

* Median values for these measurements are actually multivariate 50th percentile values.

Table 8. Dimensions of a Medium Headform (Method 3)
Full Body Weight = 72.40 Kg   Stature = 1725.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H28 menton-sellion length	118.808	5.762	118.730
H29 menton-subnasale length	72.092	4.975	71.990
H30 menton-top of head	227.529	8.011	227.100
H31 min. frontal breadth	103.746	4.721	103.440
H32 nose breadth	35.763	4.382	35.130
H33 nose protrusion	18.623	2.574	18.620
H34 pronasale-back of head	216.153	4.959	216.200
H35 pronasale-top of head	148.792	8.287	148.800
H36 sellion-back of head	194.451	2.656	194.500
H37 sellion top of head	110.027	6.522	109.900
H38 stomion-back of head	196.928	7.994	195.800
H39 stomion-top of head	183.008	7.292	182.800
H40 subnasale-back of head	201.004	5.881	200.800
H41 subnasale-sellion length	49.886	3.588	49.830
H42 subnasale-top of head	159.192	7.541	159.800
H43 tragion-back of head	98.300	4.037	98.100
H44 tragion-top of head	128.596	5.622	128.650
H45 zygion-back of head	131.435	4.465	131.350
H46 zygion-top of head	129.453	4.722	129.650
H47 zygofrontale-back of head	168.382	3.473	168.550
H48 zygofrontale-top of head	103.958	6.699	103.650

Table 9. Dimensions of a Large Headform (Method 3)
Full Body Weight = 86.10 Kg Stature = 1781.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
Head Length*			207.840
Head Breadth*			161.250
Head Circumference*			595.250
neck circumference	392.178	22.097	392.000
bitragion chin arc	335.178	12.652	335.000
bitragion coronal arc	365.365	11.532	365.000
bitragion crinion arc	338.183	10.675	338.000
bitragion frontal arc	315.431	9.022	315.000
bitragion subman. arc	313.005	15.196	313.000
bitragion subnas. arc	300.858	10:221	300.000
bizygomatic breadth	144.680	5.200	144.000
ear breadth	38.345	3.006	38.000
ear length	65.756	4.819	66.000
ear length above tragion	33.528	6.909	32.000
ear protrusion	24.487	3.529	24.000
interpupillary breadth	67.030	3.451	67.000
H1 alare-back of head	207.664	5.937	207.450
H2 alare-top of head	159.521	7.658	159.200
H3 bigonial breadth	123.009	8.048	123.200
H4 biinfraorbitale breadth	70.913	5.045	70.160
H5 biocular breadth, max	125.844	5.388	124.800
H6 bitragion breadth	149.152	5.606	149.360
H7 bizygomatic breadth	148.354	5.653	147.900
H8 cheilion-back of head	192.580	7.495	191.950
H9 cheilion-top of head	193.123	7.539	192.400
H10 chin-back of head	202.527	8.597	202.200
H11 chin-top of head	222.506	9.262	222.100
H12 crinion-back of head	191.897	7.798	192.600
H13 crinion-top of head	42.496	10.600	42.700
H14 ectoorbitale-back of head	166.763	4.559	166.550
H15 ectoorbitale-top of head	121.727	6.048	121.300
H16 frontotemporale-back of head	181.581	4.267	181.550
H17 frontotemporale-top of head	93.034	7.614	92.700
H18 glabella-back of head	208.447	3.972	208.500
H19 glabella-top of head	99.089	8.013	99.100
H20 gonion-back of head	123.120	7.180	123.150
H21 gonion-top of head	203.616	7.467	202.800
H22 infraorbitale-back of head	188.542	4.756	188.300
H23 infraorbitale-top of head	134.525	6.010	133.900
H24 lip length	57.940	4.094	57.900
H25 maximum frontal breadth	117.578	4.872	117.480
H26 menton_back of head	190.196	9.212	189.600
H27 menton-crinion length	196.311	10.780	195.800

* Median values for these measurements are actually multivariate 95th percentile values.

Table 9. Dimensions of a Large Headform (Method 3)
Full Body Weight = 86.10 Kg Stature = 1781.0 mm

Anthropometric Measurement	Mean(mm)	Standard Deviation(mm)	Median(mm)
H28 menton-sellion length	123.862	6.457	123.970
H29 menton-subnasale length	75.434	5.851	75.580
H30 menton-top of head	238.299	9.214	237.800
H31 min. frontal breadth	109.820	4.835	110.120
H32 nose breadth	37.896	4.577	36.850
H33 nose protrusion	19.322	2.411	19.330
H34 pronasale-back of head	227.458	5.899	226.900
H35 pronasale-top of head	155.840	9.000	156.100
H36 sellion-back of head	205.234	4.498	205.300
H37 sellion top of head	115.676	7.443	114.700
H38 stomion-back of head	207.660	7.963	207.100
H39 stomion-top of head	191.313	8.098	191.000
H40 subnasale-back of head	211.480	6.391	211.500
H41 subnasale-sellion length	51.191	3.608	51.010
H42 subnasale-top of head	166.237	7.892	166.400
H43 tragion-back of head	104.120	4.845	104.300
H44 tragion-top of head	134.771	5.816	134.100
H45 zygion-back of head	138.177	5.095	138.150
H46 zygion-top of head	135.189	5.651	134.900
H47 zygofrontale-back of head	178.246	4.549	178.050
H48 zygofrontale-top of head	109.584	6.461	109.550

APPENDIX C

HEADFORM SKIN & SKULL EXTERIOR DIMENSION TABLES

LIST OF TABLES

TABLE 1. SMALL HEADFORM SKIN - EXTERIOR DIMENSIONS

LEVEL -5 Z= -4.520 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	1.699	1.699	0.000
10	1.704	1.678	0.296
20	1.723	1.619	0.589
30	1.755	1.520	0.878
40	1.798	1.378	1.156
50	1.855	1.192	1.421
60	1.921	0.961	1.664
70	1.999	0.684	1.878
80	2.086	0.362	2.054
90	2.178	0.000	2.178
100	2.275	-0.395	2.241
110	2.373	-0.812	2.230
120	2.470	-1.235	2.139
130	2.559	-1.645	1.960
140	2.639	-2.021	1.696
150	2.704	-2.342	1.352
160	2.753	-2.587	0.942
170	2.784	-2.742	0.483
180	2.795	-2.795	0.000

LEVEL -4 Z= -4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	1.750	1.750	0.000
10	1.735	1.709	0.301
20	1.713	1.610	0.586
30	1.718	1.487	0.859
40	1.765	1.352	1.134
50	1.831	1.177	1.402
60	1.899	0.949	1.645
70	1.976	0.676	1.857
80	2.060	0.358	2.029
90	2.152	0.000	2.152
100	2.246	-0.390	2.211
110	2.344	-0.802	2.203
120	2.442	-1.221	2.115
130	2.535	-1.629	1.942
140	2.617	-2.005	1.682
150	2.681	-2.322	1.340
160	2.727	-2.563	0.933
170	2.754	-2.712	0.478
180	2.764	-2.764	0.000

LEVEL -3 Z= -3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.535	3.535	0.000
10	3.392	3.341	0.589
20	3.167	2.976	1.083
30	2.891	2.504	1.446
40	2.623	2.010	1.686
50	2.416	1.553	1.851
60	2.214	1.107	1.917
70	1.995	0.682	1.875
80	2.050	0.356	2.019
90	2.126	0.000	2.126
100	2.221	-0.386	2.187
110	2.311	-0.791	2.172
120	2.403	-1.201	2.081
130	2.491	-1.601	1.908
140	2.564	-1.964	1.648
150	2.610	-2.261	1.305
160	2.637	-2.478	0.902
170	2.649	-2.609	0.460
180	2.655	-2.655	0.000

LEVEL -2 Z= -2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.758	3.758	0.000
10	3.624	3.569	0.629
20	3.303	3.103	1.130
30	2.979	2.580	1.490
40	2.756	2.111	1.772
50	2.601	1.672	1.992
60	2.494	1.247	2.160
70	2.426	0.830	2.280
80	2.263	0.393	2.229
90	2.217	0.000	2.217
100	2.282	-0.396	2.248
110	2.363	-0.808	2.221
120	2.448	-1.224	2.120
130	2.528	-1.625	1.936
140	2.587	-1.982	1.663
150	2.613	-2.263	1.306
160	2.616	-2.459	0.895
170	2.612	-2.573	0.454
180	2.611	-2.611	0.000

TABLE 1. SMALL HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL -1 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.308	4.308	0.000
10	3.607	3.553	0.626
20	3.484	3.274	1.191
30	3.278	2.839	1.639
40	3.103	2.377	1.994
50	2.944	1.892	2.255
60	2.796	1.398	2.421
70	2.668	0.912	2.507
80	2.570	0.446	2.531
90	2.415	0.000	2.415
100	2.591	-0.450	2.552
110	2.715	-0.929	2.552
120	2.654	-1.327	2.299
130	2.742	-1.763	2.101
140	2.805	-2.149	1.803
150	2.826	-2.447	1.413
160	2.821	-2.651	0.965
170	2.811	-2.768	0.488
180	2.808	-2.808	0.000

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.063	4.063	0.000
10	3.430	3.378	0.596
20	3.334	3.133	1.140
30	3.253	2.817	1.626
40	3.170	2.428	2.038
50	3.092	1.987	2.368
60	3.003	1.501	2.601
70	2.901	0.992	2.726
80	2.795	0.485	2.753
90	2.702	0.000	2.702
100	2.839	-0.493	2.796
110	2.975	-1.018	2.796
120	2.985	-1.493	2.585
130	3.111	-2.000	2.383
140	3.212	-2.461	2.065
150	3.262	-2.825	1.631
160	3.280	-3.082	1.122
170	3.286	-3.236	0.571
180	3.290	-3.290	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.741	3.741	0.000
10	3.620	3.565	0.629
20	3.441	3.234	1.177
30	3.539	3.065	1.770
40	3.376	2.586	2.170
50	3.206	2.061	2.456
60	3.100	1.550	2.685
70	3.013	1.031	2.832
80	2.945	0.511	2.900
90	2.901	0.000	2.901
100	2.968	-0.515	2.923
110	3.078	-1.053	2.892
120	3.225	-1.612	2.793
130	3.386	-2.177	2.594
140	3.522	-2.698	2.264
150	3.598	-3.116	1.799
160	3.634	-3.415	1.243
170	3.654	-3.599	0.635
180	3.663	-3.663	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.708	3.708	0.000
10	3.724	3.668	0.647
20	3.690	3.467	1.262
30	3.536	3.062	1.768
40	3.321	2.544	2.135
50	3.149	2.024	2.413
60	3.038	1.519	2.631
70	2.969	1.015	2.790
80	2.928	0.508	2.883
90	2.912	0.000	2.912
100	2.978	-0.517	2.933
110	3.090	-1.057	2.904
120	3.240	-1.620	2.806
130	3.401	-2.186	2.605
140	3.535	-2.708	2.272
150	3.613	-3.129	1.806
160	3.652	-3.432	1.249
170	3.675	-3.619	0.638
180	3.685	-3.685	0.000

TABLE 1. SMALL HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.376	3.376	0.000
10	3.396	3.344	0.590
20	3.382	3.178	1.157
30	3.283	2.843	1.642
40	3.124	2.393	2.008
50	2.981	1.916	2.284
60	2.896	1.448	2.508
70	2.847	0.974	2.676
80	2.821	0.490	2.778
90	2.813	0.000	2.813
100	2.877	-0.500	2.834
110	2.976	-1.018	2.796
120	3.096	-1.548	2.681
130	3.214	-2.066	2.462
140	3.303	-2.530	2.123
150	3.347	-2.899	1.674
160	3.363	-3.160	1.150
170	3.369	-3.318	0.585
180	3.372	-3.372	0.000

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.358	2.358	0.000
10	2.397	2.361	0.416
20	2.433	2.287	0.832
30	2.406	2.084	1.203
40	2.337	1.790	1.502
50	2.283	1.467	1.749
60	2.272	1.136	1.968
70	2.276	0.779	2.139
80	2.285	0.397	2.250
90	2.289	0.000	2.289
100	2.346	-0.407	2.310
110	2.419	-0.827	2.274
120	2.502	-1.251	2.167
130	2.574	-1.655	1.972
140	2.618	-2.005	1.683
150	2.621	-2.270	1.311
160	2.603	-2.446	0.890
170	2.585	-2.546	0.449
180	2.581	-2.581	0.000

Notes:

1. Apex is located at (-0.180,0.000,4.800) for (X,Y,Z) or (0.180,180,4.800) for (R,θ,Z).

2. Headform is symmetrical about the mid-sagittal plane.

TABLE 2. SMALL HEADFORM SKULL - EXTERIOR DIMENSIONS

LEVEL -4 Z= -3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.159	3.159	0.000
10	3.028	2.985	0.510
20	2.793	2.634	0.929
30	2.552	2.227	1.246
40	2.338	1.814	1.475
50	2.164	1.416	1.636
60	---	---	---
70	---	---	---
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -3 Z= -2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.195	3.195	0.000
10	3.093	3.049	0.521
20	2.901	2.736	0.965
30	2.697	2.353	1.317
40	2.500	1.939	1.577
50	2.326	1.523	1.758
60	2.196	1.124	1.886
70	2.080	0.731	1.947
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -2 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.204	3.204	0.000
10	3.136	3.091	0.528
20	2.995	2.824	0.996
30	2.825	2.466	1.380
40	2.643	2.051	1.668
50	2.481	1.624	1.876
60	2.362	1.209	2.029
70	2.265	0.796	2.120
80	2.175	0.389	2.139
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -1 Z= -0.326 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.196	3.196	0.000
10	3.152	3.107	0.531
20	3.046	2.873	1.013
30	2.895	2.527	1.414
40	2.719	2.109	1.715
50	2.573	1.684	1.945
60	2.466	1.262	2.118
70	2.391	0.841	2.238
80	2.320	0.415	2.283
90	2.237	0.000	2.237
100	2.297	-0.411	2.260
110	2.381	-0.837	2.229
120	2.484	-1.271	2.134
130	2.594	-1.698	1.961
140	2.683	-2.082	1.693
150	2.729	-2.382	1.333
160	2.748	-2.591	0.914
170	2.754	-2.714	0.464
180	2.757	-2.757	0.000

TABLE 2. SMALL HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.200	3.200	0.000
10	3.169	3.123	0.534
20	3.074	2.898	1.022
30	2.914	2.543	1.423
40	2.753	2.136	1.737
50	2.613	1.711	1.976
60	2.511	1.285	2.157
70	2.445	0.860	2.289
80	2.385	0.427	2.347
90	2.324	0.000	2.324
100	2.384	-0.427	2.346
110	2.474	-0.870	2.316
120	2.588	-1.325	2.223
130	2.711	-1.775	2.050
140	2.815	-2.184	1.776
150	2.873	-2.507	1.403
160	2.901	-2.736	0.965
170	2.914	-2.872	0.491
180	2.920	-2.920	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.335	3.335	0.000
10	3.292	3.245	0.555
20	3.236	3.052	1.077
30	3.068	2.678	1.498
40	2.897	2.248	1.828
50	2.735	1.791	2.068
60	2.628	1.345	2.257
70	2.559	0.900	2.395
80	2.519	0.451	2.478
90	2.501	0.000	2.501
100	2.562	-0.459	2.521
110	2.665	-0.937	2.494
120	2.804	-1.435	2.409
130	2.961	-1.939	2.239
140	3.098	-2.404	1.954
150	3.181	-2.776	1.553
160	3.227	-3.044	1.074
170	3.254	-3.207	0.548
180	3.265	-3.265	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.261	3.261	0.000
10	3.272	3.225	0.551
20	3.235	3.051	1.076
30	3.095	2.701	1.511
40	2.898	2.249	1.828
50	2.734	1.790	2.067
60	2.625	1.344	2.255
70	2.556	0.899	2.393
80	2.515	0.450	2.474
90	2.500	0.000	2.500
100	2.559	-0.458	2.518
110	2.662	-0.936	2.492
120	2.800	-1.433	2.405
130	2.951	-1.931	2.231
140	3.078	-2.388	1.942
150	3.159	-2.757	1.543
160	3.206	-3.023	1.066
170	3.234	-3.187	0.545
180	3.245	-3.245	0.000

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.828	2.828	0.000
10	2.847	2.806	0.479
20	2.836	2.675	0.943
30	2.753	2.403	1.344
40	2.620	2.033	1.653
50	2.498	1.635	1.888
60	2.425	1.241	2.083
70	2.383	0.838	2.230
80	2.360	0.422	2.322
90	2.353	0.000	2.353
100	2.410	-0.431	2.371
110	2.495	-0.877	2.336
120	2.600	-1.331	2.234
130	2.704	-1.770	2.044
140	2.784	-2.160	1.756
150	2.825	-2.466	1.380
160	2.841	-2.679	0.945
170	2.845	-2.805	0.479
180	2.849	-2.849	0.000

TABLE 2. SMALL HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	1.466	1.466	0.000
10	1.502	1.481	0.253
20	1.543	1.455	0.513
30	1.536	1.340	0.750
40	1.498	1.163	0.945
50	1.477	0.967	1.117
60	1.491	0.763	1.281
70	1.512	0.532	1.416
80	1.529	0.274	1.504
90	1.537	0.000	1.537
100	1.584	-0.284	1.558
110	1.646	-0.579	1.541
120	1.719	-0.880	1.477
130	1.787	-1.170	1.351
140	1.833	-1.422	1.156
150	1.844	-1.609	0.900
160	1.839	-1.734	0.612
170	1.833	-1.807	0.309
180	1.832	-1.832	0.000

Notes:

1. Apex is located at (-0.160,0.000,4.392) for (X,Y,Z) or (0.160,180,4.392) for (R,θ,Z).
2. Headform is symmetrical about the mid-sagittal plane.

TABLE 3. MEDIUM HEADFORM SKIN - EXTERIOR DIMENSIONS

LEVEL -5 Z= -4.850 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	1.792	1.792	0.000
10	1.798	1.770	0.312
20	1.818	1.708	0.622
30	1.852	1.603	0.926
40	1.897	1.453	1.219
50	1.956	1.257	1.499
60	2.026	1.013	1.755
70	2.109	0.721	1.981
80	2.200	0.382	2.167
90	2.298	0.000	2.298
100	2.400	-0.417	2.364
110	2.504	-0.856	2.353
120	2.605	-1.303	2.256
130	2.699	-1.735	2.067
140	2.783	-2.132	1.789
150	2.852	-2.470	1.426
160	2.904	-2.729	0.993
170	2.937	-2.892	0.510
180	2.948	-2.948	0.000

LEVEL -4 Z= -4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.095	2.095	0.000
10	2.071	2.040	0.360
20	1.986	1.866	0.679
30	1.887	1.635	0.944
40	1.873	1.435	1.204
50	1.934	1.243	1.481
60	2.005	1.003	1.737
70	2.081	0.712	1.956
80	2.161	0.375	2.129
90	2.259	0.000	2.259
100	2.356	-0.409	2.320
110	2.458	-0.841	2.310
120	2.561	-1.280	2.218
130	2.659	-1.709	2.037
140	2.744	-2.102	1.764
150	2.808	-2.431	1.404
160	2.852	-2.680	0.975
170	2.877	-2.833	0.500
180	2.887	-2.887	0.000

LEVEL -3 Z= -3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.700	3.700	0.000
10	3.534	3.481	0.614
20	3.302	3.102	1.129
30	3.043	2.636	1.522
40	2.789	2.136	1.793
50	2.590	1.665	1.984
60	2.459	1.230	2.130
70	2.149	0.735	2.020
80	2.173	0.377	2.140
90	2.260	0.000	2.260
100	2.347	-0.408	2.311
110	2.440	-0.835	2.293
120	2.534	-1.267	2.195
130	2.625	-1.688	2.011
140	2.699	-2.068	1.735
150	2.744	-2.376	1.372
160	2.767	-2.600	0.946
170	2.776	-2.734	0.482
180	2.780	-2.780	0.000

LEVEL -2 Z= -2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.091	4.091	0.000
10	3.856	3.798	0.670
20	3.490	3.279	1.194
30	3.173	2.748	1.586
40	2.949	2.259	1.896
50	2.787	1.791	2.135
60	2.670	1.335	2.312
70	2.592	0.886	2.436
80	2.519	0.437	2.481
90	2.350	0.000	2.350
100	2.427	-0.421	2.390
110	2.511	-0.859	2.360
120	2.600	-1.300	2.252
130	2.683	-1.725	2.056
140	2.745	-2.103	1.764
150	2.770	-2.399	1.385
160	2.771	-2.604	0.948
170	2.765	-2.723	0.480
180	2.763	-2.763	0.000

TABLE 3. MEDIUM HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL -1 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.685	4.685	0.000
10	3.808	3.751	0.661
20	3.690	3.467	1.262
30	3.479	3.013	1.740
40	3.297	2.525	2.119
50	3.129	2.011	2.397
60	2.971	1.486	2.573
70	2.832	0.968	2.661
80	2.725	0.473	2.683
90	2.567	0.000	2.567
100	2.751	-0.478	2.709
110	2.883	-0.986	2.709
120	2.822	-1.411	2.444
130	2.916	-1.875	2.234
140	2.985	-2.286	1.918
150	3.008	-2.605	1.504
160	3.003	-2.822	1.027
170	2.993	-2.948	0.520
180	2.990	-2.990	0.000

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.286	4.286	0.000
10	3.618	3.564	0.628
20	3.517	3.305	1.203
30	3.431	2.971	1.716
40	3.344	2.562	2.149
50	3.261	2.096	2.498
60	3.168	1.584	2.743
70	3.060	1.047	2.875
80	2.948	0.512	2.904
90	2.850	0.000	2.850
100	2.995	-0.520	2.949
110	3.138	-1.073	2.949
120	3.149	-1.575	2.727
130	3.282	-2.109	2.514
140	3.389	-2.596	2.178
150	3.441	-2.980	1.721
160	3.460	-3.251	1.183
170	3.466	-3.413	0.602
180	3.470	-3.470	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.929	3.929	0.000
10	3.768	3.711	0.654
20	3.562	3.347	1.218
30	3.672	3.180	1.836
40	3.563	2.729	2.290
50	3.383	2.175	2.592
60	3.272	1.636	2.834
70	3.178	1.087	2.986
80	3.103	0.539	3.056
90	3.052	0.000	3.052
100	3.198	-0.555	3.149
110	3.347	-1.145	3.145
120	3.392	-1.696	2.938
130	3.561	-2.289	2.728
140	3.702	-2.836	2.380
150	3.782	-3.275	1.891
160	3.820	-3.589	1.306
170	3.840	-3.782	0.667
180	3.850	-3.850	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.931	3.931	0.000
10	3.949	3.889	0.686
20	3.911	3.675	1.338
30	3.741	3.240	1.871
40	3.509	2.688	2.256
50	3.328	2.139	2.549
60	3.210	1.605	2.780
70	3.136	1.073	2.947
80	3.092	0.537	3.045
90	3.075	0.000	3.075
100	3.144	-0.546	3.096
110	3.262	-1.116	3.066
120	3.422	-1.711	2.963
130	3.596	-2.311	2.754
140	3.740	-2.865	2.404
150	3.824	-3.312	1.912
160	3.866	-3.633	1.322
170	3.890	-3.831	0.676
180	3.901	-3.901	0.000

TABLE 3. MEDIUM HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.671	3.671	0.000
10	3.690	3.634	0.641
20	3.669	3.448	1.255
30	3.552	3.077	1.776
40	3.371	2.582	2.167
50	3.208	2.062	2.458
60	3.109	1.554	2.692
70	3.051	1.043	2.867
80	3.018	0.524	2.972
90	3.007	0.000	3.007
100	3.076	-0.534	3.030
110	3.185	-1.089	2.993
120	3.319	-1.660	2.875
130	3.455	-2.221	2.647
140	3.561	-2.728	2.289
150	3.617	-3.132	1.808
160	3.641	-3.421	1.245
170	3.653	-3.598	0.634
180	3.659	-3.659	0.000

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.889	2.889	0.000
10	2.924	2.880	0.508
20	2.946	2.768	1.008
30	2.895	2.507	1.448
40	2.795	2.141	1.796
50	2.708	1.741	2.075
60	2.670	1.335	2.312
70	2.658	0.909	2.497
80	2.654	0.461	2.614
90	2.655	0.000	2.655
100	2.718	-0.472	2.677
110	2.802	-0.958	2.633
120	2.898	-1.449	2.510
130	2.984	-1.918	2.286
140	3.039	-2.328	1.953
150	3.051	-2.642	1.525
160	3.037	-2.854	1.039
170	3.021	-2.976	0.525
180	3.018	-3.018	0.000

LEVEL +5 Z= 5.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	0.854	0.854	0.000
10	0.889	0.876	0.154
20	0.940	0.884	0.322
30	0.960	0.831	0.480
40	0.956	0.732	0.614
50	0.969	0.623	0.742
60	1.017	0.509	0.881
70	1.076	0.368	1.012
80	1.125	0.195	1.108
90	1.147	0.000	1.147
100	1.197	-0.208	1.179
110	1.265	-0.433	1.189
120	1.345	-0.672	1.164
130	1.422	-0.914	1.090
140	1.475	-1.130	0.948
150	1.495	-1.294	0.747
160	1.497	-1.407	0.512
170	1.500	-1.477	0.261
180	1.504	-1.504	0.000

TABLE 3. MEDIUM HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

Notes:

1. Apex is located at (-0.190,0.000,5.150) for (X,Y,Z) or (0.190,180,5.150) for (R,θ,Z).
2. Headform is symmetrical about the mid-sagittal plane.

TABLE 4. MEDIUM HEADFORM SKULL - EXTERIOR DIMENSIONS

LEVEL -4 Z= -3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.341	3.341	0.000
10	3.209	3.163	0.540
20	2.969	2.800	0.988
30	2.723	2.376	1.330
40	2.501	1.940	1.578
50	2.317	1.516	1.751
60	2.177	1.114	1.870
70	---	---	---
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -3 Z= -2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.374	3.374	0.000
10	3.271	3.224	0.551
20	3.076	2.900	1.023
30	2.865	2.500	1.399
40	2.659	2.063	1.677
50	2.477	1.621	1.872
60	2.341	1.198	2.011
70	2.219	0.780	2.077
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -2 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.379	3.379	0.000
10	3.310	3.263	0.557
20	3.165	2.984	1.053
30	2.988	2.608	1.459
40	2.797	2.170	1.765
50	2.628	1.720	1.986
60	2.504	1.282	2.151
70	2.403	0.845	2.249
80	2.310	0.414	2.273
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -1 Z= -0.350 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.371	3.371	0.000
10	3.325	3.278	0.560
20	3.214	3.031	1.069
30	3.054	2.665	1.491
40	2.868	2.225	1.809
50	2.714	1.776	2.052
60	2.601	1.331	2.234
70	2.522	0.887	2.361
80	2.448	0.438	2.408
90	2.359	0.000	2.359
100	2.423	-0.434	2.384
110	2.512	-0.883	2.351
120	2.620	-1.341	2.251
130	2.736	-1.791	2.068
140	2.830	-2.196	1.786
150	2.879	-2.513	1.406
160	2.898	-2.733	0.964
170	2.905	-2.863	0.489
180	2.908	-2.908	0.000

TABLE 4. MEDIUM HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.376	3.376	0.000
10	3.343	3.295	0.563
20	3.242	3.057	1.078
30	3.074	2.682	1.501
40	2.904	2.253	1.832
50	2.757	1.804	2.084
60	2.649	1.356	2.276
70	2.579	0.907	2.414
80	2.516	0.450	2.475
90	2.451	0.000	2.451
100	2.515	-0.450	2.475
110	2.610	-0.918	2.443
120	2.730	-1.397	2.345
130	2.860	-1.872	2.162
140	2.969	-2.304	1.873
150	3.031	-2.645	1.480
160	3.060	-2.886	1.018
170	3.073	-3.029	0.518
180	3.080	-3.080	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.503	3.503	0.000
10	3.449	3.400	0.581
20	3.394	3.200	1.129
30	3.210	2.801	1.567
40	3.043	2.361	1.920
50	2.876	1.882	2.174
60	2.764	1.415	2.375
70	2.694	0.947	2.522
80	2.652	0.475	2.609
90	2.633	0.000	2.633
100	2.696	-0.483	2.653
110	2.805	-0.986	2.626
120	2.951	-1.510	2.535
130	3.115	-2.039	2.355
140	3.258	-2.528	2.055
150	3.345	-2.920	1.633
160	3.394	-3.200	1.129
170	3.421	-3.372	0.576
180	3.433	-3.433	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.466	3.466	0.000
10	3.478	3.428	0.586
20	3.437	3.241	1.143
30	3.282	2.864	1.602
40	3.068	2.380	1.936
50	2.894	1.894	2.187
60	2.777	1.421	2.386
70	2.703	0.950	2.530
80	2.658	0.476	2.615
90	2.641	0.000	2.641
100	2.704	-0.484	2.660
110	2.813	-0.989	2.634
120	2.961	-1.516	2.544
130	3.125	-2.045	2.362
140	3.264	-2.533	2.059
150	3.352	-2.926	1.637
160	3.403	-3.209	1.132
170	3.433	-3.384	0.578
180	3.446	-3.446	0.000

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.130	3.130	0.000
10	3.146	3.101	0.530
20	3.126	2.948	1.040
30	3.025	2.640	1.477
40	2.867	2.224	1.809
50	2.723	1.782	2.058
60	2.633	1.348	2.262
70	2.579	0.907	2.415
80	2.550	0.456	2.508
90	2.540	0.000	2.540
100	2.601	-0.466	2.559
110	2.697	-0.948	2.524
120	2.816	-1.441	2.419
130	2.937	-1.922	2.220
140	3.033	-2.353	1.913
150	3.087	-2.694	1.507
160	3.112	-2.934	1.035
170	3.123	-3.079	0.526
180	3.129	-3.129	0.000

TABLE 4. MEDIUM HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.094	2.094	0.000
10	2.130	2.100	0.359
20	2.162	2.038	0.719
30	2.132	1.861	1.041
40	2.064	1.601	1.302
50	2.011	1.316	1.520
60	1.997	1.022	1.716
70	1.997	0.702	1.870
80	2.002	0.358	1.969
90	2.005	0.000	2.005
100	2.058	-0.368	2.025
110	2.129	-0.749	1.993
120	2.212	-1.132	1.900
130	2.288	-1.498	1.730
140	2.340	-1.815	1.476
150	2.354	-2.054	1.149
160	2.346	-2.212	0.780
170	2.336	-2.302	0.393
180	2.334	-2.334	0.000

Notes:

1. Apex is located at (-0.169,0.000,4.712) for (X,Y,Z) or (0.169,180,4.712) for (R,θ,Z).
2. Headform is symmetrical about the mid-sagittal plane.

TABLE 5. LARGE HEADFORM SKIN - EXTERIOR DIMENSIONS

LEVEL -5		Z= -5.020 (in)	
θ(deg)	R(in)	X(in)	Y(in)
0	1.874	1.874	0.000
10	1.880	1.852	0.326
20	1.901	1.787	0.648
30	1.935	1.677	0.966
40	1.982	1.520	1.272
50	2.043	1.315	1.563
60	2.115	1.060	1.830
70	2.200	0.754	2.067
80	2.295	0.400	2.260
90	2.397	0.000	2.397
100	2.504	-0.436	2.465
110	2.612	-0.896	2.454
120	2.719	-1.363	2.353
130	2.818	-1.815	2.156
140	2.908	-2.230	1.866
150	2.981	-2.584	1.487
160	3.037	-2.854	1.036
170	3.071	-3.025	0.532
180	3.084	-3.084	0.000

LEVEL -4		Z= -4.000 (in)	
θ(deg)	R(in)	X(in)	Y(in)
0	3.710	3.710	0.000
10	3.542	3.489	0.613
20	3.175	2.985	1.083
30	2.476	2.146	1.235
40	2.006	1.539	1.287
50	2.024	1.303	1.549
60	2.097	1.051	1.814
70	2.173	0.745	2.041
80	2.251	0.392	2.216
90	2.352	0.000	2.352
100	2.452	-0.427	2.415
110	2.559	-0.877	2.404
120	2.666	-1.336	2.307
130	2.769	-1.783	2.119
140	2.859	-2.193	1.834
150	2.924	-2.534	1.459
160	2.969	-2.791	1.013
170	2.994	-2.949	0.518
180	3.004	-3.004	0.000

LEVEL -3		Z= -3.000 (in)	
θ(deg)	R(in)	X(in)	Y(in)
0	3.888	3.888	0.000
10	3.699	3.643	0.641
20	3.444	3.237	1.175
30	3.176	2.752	1.584
40	2.919	2.239	1.873
50	2.717	1.749	2.079
60	2.586	1.296	2.238
70	2.316	0.794	2.176
80	2.279	0.397	2.245
90	2.352	0.000	2.352
100	2.451	-0.427	2.414
110	2.548	-0.874	2.394
120	2.647	-1.326	2.290
130	2.742	-1.765	2.098
140	2.819	-2.162	1.809
150	2.864	-2.482	1.429
160	2.887	-2.714	0.985
170	2.896	-2.852	0.501
180	2.899	-2.899	0.000

LEVEL -2		Z= -2.000 (in)	
θ(deg)	R(in)	X(in)	Y(in)
0	4.301	4.301	0.000
10	4.027	3.966	0.697
20	3.656	3.437	1.247
30	3.333	2.889	1.663
40	3.102	2.379	1.990
50	2.931	1.887	2.243
60	2.807	1.406	2.429
70	2.720	0.933	2.555
80	2.659	0.463	2.618
90	2.462	0.000	2.462
100	2.541	-0.443	2.503
110	2.630	-0.902	2.471
120	2.723	-1.365	2.357
130	2.812	-1.811	2.152
140	2.877	-2.207	1.846
150	2.904	-2.516	1.449
160	2.905	-2.730	0.991
170	2.898	-2.854	0.502
180	2.896	-2.896	0.000

TABLE 5. LARGE HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL -1 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.936	4.936	0.000
10	3.986	3.926	0.690
20	3.865	3.633	1.319
30	3.646	3.160	1.819
40	3.456	2.650	2.217
50	3.279	2.111	2.509
60	3.111	1.559	2.693
70	2.963	1.016	2.783
80	2.849	0.496	2.805
90	2.687	0.000	2.687
100	2.878	-0.501	2.834
110	3.017	-1.034	2.834
120	2.956	-1.481	2.558
130	3.057	-1.968	2.339
140	3.131	-2.401	2.009
150	3.157	-2.736	1.575
160	3.154	-2.965	1.076
170	3.145	-3.097	0.545
180	3.142	-3.142	0.000

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.483	4.483	0.000
10	3.785	3.727	0.655
20	3.678	3.457	1.255
30	3.586	3.108	1.789
40	3.494	2.679	2.242
50	3.405	2.193	2.606
60	3.306	1.657	2.861
70	3.193	1.095	2.999
80	3.075	0.536	3.028
90	2.973	0.000	2.973
100	3.124	-0.544	3.076
110	3.274	-1.123	3.076
120	3.287	-1.647	2.844
130	3.427	-2.206	2.622
140	3.540	-2.715	2.272
150	3.597	-3.117	1.795
160	3.618	-3.401	1.234
170	3.625	-3.570	0.628
180	3.630	-3.630	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.101	4.101	0.000
10	3.915	3.856	0.678
20	3.724	3.500	1.270
30	3.808	3.300	1.900
40	3.722	2.854	2.388
50	3.533	2.275	2.703
60	3.415	1.711	2.956
70	3.315	1.137	3.114
80	3.234	0.563	3.185
90	3.179	0.000	3.179
100	3.360	-0.585	3.308
110	3.514	-1.205	3.301
120	3.535	-1.772	3.060
130	3.712	-2.390	2.840
140	3.861	-2.961	2.478
150	3.946	-3.420	1.969
160	3.987	-3.747	1.360
170	4.009	-3.948	0.694
180	4.019	-4.019	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	4.120	4.120	0.000
10	4.139	4.076	0.717
20	4.097	3.852	1.398
30	3.914	3.392	1.953
40	3.668	2.813	2.354
50	3.477	2.239	2.660
60	3.352	1.680	2.901
70	3.273	1.122	3.075
80	3.226	0.562	3.177
90	3.208	0.000	3.208
100	3.280	-0.571	3.230
110	3.404	-1.167	3.198
120	3.573	-1.790	3.092
130	3.757	-2.419	2.875
140	3.912	-3.000	2.510
150	4.002	-3.468	1.997
160	4.047	-3.804	1.381
170	4.073	-4.011	0.705
180	4.084	-4.084	0.000

TABLE 5. LARGE HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.885	3.885	0.000
10	3.903	3.844	0.676
20	3.877	3.645	1.323
30	3.749	3.249	1.870
40	3.550	2.723	2.278
50	3.374	2.173	2.582
60	3.266	1.636	2.826
70	3.201	1.097	3.007
80	3.164	0.551	3.116
90	3.151	0.000	3.151
100	3.224	-0.561	3.175
110	3.340	-1.145	3.138
120	3.486	-1.747	3.016
130	3.635	-2.340	2.781
140	3.752	-2.878	2.408
150	3.816	-3.308	1.904
160	3.847	-3.616	1.312
170	3.863	-3.804	0.669
180	3.870	-3.870	0.000

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.183	3.183	0.000
10	3.216	3.168	0.557
20	3.230	3.036	1.102
30	3.165	2.743	1.579
40	3.046	2.336	1.955
50	2.940	1.893	2.250
60	2.887	1.447	2.499
70	2.865	0.982	2.691
80	2.856	0.497	2.812
90	2.854	0.000	2.854
100	2.921	-0.509	2.877
110	3.013	-1.033	2.830
120	3.120	-1.563	2.700
130	3.217	-2.071	2.461
140	3.282	-2.517	2.106
150	3.302	-2.861	1.647
160	3.293	-3.096	1.123
170	3.281	-3.231	0.568
180	3.278	-3.278	0.000

LEVEL +5 Z= 5.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	1.460	1.460	0.000
10	1.504	1.482	0.261
20	1.561	1.468	0.533
30	1.570	1.360	0.783
40	1.545	1.185	0.992
50	1.542	0.993	1.180
60	1.581	0.792	1.368
70	1.627	0.558	1.528
80	1.662	0.289	1.637
90	1.677	0.000	1.677
100	1.733	-0.302	1.707
110	1.807	-0.620	1.697
120	1.890	-0.947	1.635
130	1.967	-1.266	1.505
140	2.014	-1.545	1.293
150	2.024	-1.754	1.010
160	2.015	-1.894	0.687
170	2.007	-1.977	0.348
180	2.007	-2.007	0.000

TABLE 5. LARGE HEADFORM SKIN - EXTERIOR DIMENSIONS (cont.)

Notes:

1. Apex is located at (-0.199,0.000,5.330) for (X,Y,Z) or (0.199,180,5.330) for (R,θ,Z).

2. Headform is symmetrical about the mid-sagittal plane.

TABLE 6. LARGE HEADFORM SKULL - EXTERIOR DIMENSIONS

LEVEL -4 Z= -3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.499	3.499	0.000
10	3.363	3.316	0.565
20	3.116	2.940	1.034
30	2.862	2.499	1.394
40	2.630	2.043	1.657
50	2.436	1.597	1.839
60	2.289	1.174	1.965
70	---	---	---
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -3 Z= -2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.530	3.530	0.000
10	3.425	3.376	0.575
20	3.223	3.041	1.069
30	3.004	2.623	1.463
40	2.789	2.166	1.756
50	2.598	1.703	1.961
60	2.455	1.259	2.107
70	2.327	0.820	2.177
80	---	---	---
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -2 Z= -1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.533	3.533	0.000
10	3.463	3.413	0.582
20	3.312	3.124	1.099
30	3.127	2.731	1.523
40	2.926	2.273	1.843
50	2.749	1.802	2.076
60	2.619	1.343	2.248
70	2.514	0.886	2.353
80	2.417	0.434	2.377
90	---	---	---
100	---	---	---
110	---	---	---
120	---	---	---
130	---	---	---
140	---	---	---
150	---	---	---
160	---	---	---
170	---	---	---
180	---	---	---

LEVEL -1 Z= -0.362 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.526	3.526	0.000
10	3.478	3.429	0.584
20	3.360	3.170	1.115
30	3.192	2.788	1.555
40	2.996	2.327	1.887
50	2.834	1.858	2.140
60	2.715	1.392	2.330
70	2.631	0.927	2.462
80	2.553	0.458	2.512
90	2.461	0.000	2.461
100	2.528	-0.454	2.486
110	2.621	-0.924	2.452
120	2.735	-1.403	2.348
130	2.857	-1.873	2.157
140	2.957	-2.297	1.862
150	3.009	-2.628	1.466
160	3.031	-2.859	1.006
170	3.038	-2.995	0.510
180	3.042	-3.042	0.000

TABLE 6. LARGE HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL 0 Z= 0.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.531	3.531	0.000
10	3.496	3.446	0.587
20	3.390	3.198	1.125
30	3.213	2.806	1.565
40	3.034	2.357	1.911
50	2.879	1.887	2.174
60	2.765	1.418	2.374
70	2.691	0.948	2.518
80	2.624	0.471	2.582
90	2.557	0.000	2.557
100	2.624	-0.471	2.581
110	2.723	-0.960	2.548
120	2.849	-1.461	2.446
130	2.987	-1.958	2.255
140	3.102	-2.410	1.954
150	3.168	-2.767	1.544
160	3.200	-3.018	1.062
170	3.214	-3.169	0.540
180	3.222	-3.222	0.000

LEVEL +1 Z= 1.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.656	3.656	0.000
10	3.595	3.544	0.604
20	3.539	3.338	1.174
30	3.343	2.919	1.629
40	3.173	2.464	1.998
50	2.998	1.966	2.264
60	2.882	1.478	2.474
70	2.808	0.990	2.628
80	2.763	0.496	2.719
90	2.743	0.000	2.743
100	2.810	-0.504	2.764
110	2.923	-1.030	2.735
120	3.076	-1.578	2.641
130	3.249	-2.130	2.453
140	3.399	-2.640	2.140
150	3.491	-3.049	1.701
160	3.543	-3.342	1.175
170	3.572	-3.521	0.600
180	3.584	-3.584	0.000

LEVEL +2 Z= 2.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.636	3.636	0.000
10	3.648	3.596	0.613
20	3.604	3.400	1.196
30	3.437	3.001	1.674
40	3.209	2.493	2.021
50	3.025	1.983	2.284
60	2.902	1.489	2.491
70	2.822	0.995	2.641
80	2.774	0.498	2.729
90	2.757	0.000	2.757
100	2.822	-0.507	2.776
110	2.937	-1.035	2.748
120	3.094	-1.587	2.656
130	3.267	-2.142	2.467
140	3.417	-2.654	2.152
150	3.512	-3.067	1.711
160	3.566	-3.364	1.183
170	3.599	-3.548	0.604
180	3.612	-3.612	0.000

LEVEL +3 Z= 3.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	3.333	3.333	0.000
10	3.348	3.300	0.562
20	3.323	3.135	1.102
30	3.210	2.803	1.564
40	3.035	2.358	1.912
50	2.877	1.887	2.172
60	2.777	1.425	2.384
70	2.717	0.958	2.542
80	2.682	0.482	2.639
90	2.671	0.000	2.671
100	2.735	-0.491	2.691
110	2.838	-1.000	2.656
120	2.967	-1.522	2.547
130	3.101	-2.033	2.341
140	3.208	-2.492	2.020
150	3.271	-2.856	1.594
160	3.302	-3.115	1.096
170	3.318	-3.271	0.557
180	3.326	-3.326	0.000

TABLE 6. LARGE HEADFORM SKULL - EXTERIOR DIMENSIONS (cont.)

LEVEL +4 Z= 4.000 (in)

θ(deg)	R(in)	X(in)	Y(in)
0	2.405	2.405	0.000
10	2.440	2.405	0.410
20	2.464	2.325	0.818
30	2.422	2.115	1.180
40	2.336	1.814	1.471
50	2.264	1.484	1.709
60	2.235	1.146	1.919
70	2.225	0.784	2.082
80	2.223	0.399	2.187
90	2.224	0.000	2.224
100	2.282	-0.410	2.244
110	2.359	-0.832	2.208
120	2.451	-1.257	2.104
130	2.536	-1.663	1.915
140	2.595	-2.015	1.634
150	2.614	-2.283	1.273
160	2.608	-2.460	0.865
170	2.599	-2.562	0.437
180	2.597	-2.597	0.000

Notes:

1. Apex is located at (-0.177,0.000,4.877) for (X,Y,Z) or (0.177,180,4.877) for (R,θ,Z).
2. Headform is symmetrical about the mid-sagittal plane.

Received 2/8/2000

DEPARTMENT OF THE ARMY
US ARMY MEDICAL RESEARCH AND MATERIEL COMMAND
504 SCOTT STREET
FORT DETRICK, MARYLAND 21702-5012

REPLY TO
ATTENTION OF:

MCMR-RMI-S (70-1y) 21 Jan 00

MEMORANDUM FOR Administrator, Defense Technical Information Center, ATTN: DTIC-OCA, 8725 John J. Kingman Road, Fort Belvoir, VA 22060-6218

SUBJECT: Request Change in Distribution Statement

1. The U.S. Army Medical Research and Materiel Command has reexamined the need for the limitation assigned to technical reports written for the attached Awards. Request the limited distribution statements for Accession Document Numbers listed be changed to "Approved for public release; distribution unlimited." These reports should be released to the National Technical Information Service.

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FOR THE COMMANDER:

Phyllis Rinehart

Encl
as

PHYLIS M. RINEHART
Deputy Chief of Staff for
Information Management